Reducing Embodied Carbon in Buildings

Low-Cost, High-Value Opportunities

Report / July 2021

Authors & Acknowledgments

Authors

Rebecca Esau
Matt Jungclaus
Victor Olgyay
Audrey Rempher

Authors listed alphabetically. All authors from RMI unless otherwise noted.

Contacts

Victor Olgyay, **volgyay@rmi.org**
Rebecca Esau, **resau@rmi.org**

Copyrights and Citation

Matt Jungclaus, Rebecca Esau, Victor Olgyay, and Audrey Rempher, *Reducing Embodied Carbon in Buildings: Low-Cost, High-Value Opportunities,* RMI, 2021, **http://www.rmi.org/insight/reducing-embodied-carbon-in-buildings**.

Acknowledgments

We would like to thank Skanska for providing material and cost information based on anonymized project data, and for conducting an EC3 analysis of the three case studies included in the report. We would like to recognize the following members of the Skanska team for sharing key insights and reviewing the report:

Mark Chen
Steve Clem
Elaine Lai
Tolga Tutar

We thank the following individuals for their contributions to and review of the report:

Monika Henn, Urban Land Institute
Dirk Kestner, Walter P. Moore
Meghan Lewis, Carbon Leadership Forum
Marta Schantz, Urban Land Institute

We thank the following additional individuals and organizations for participating in interviews during the research phase of this report:

Arup
Bruce King, PE - Ecological Building Network
Thornton Tomasetti
Kieran Timberlake
Erin McDade, Architecture 2030

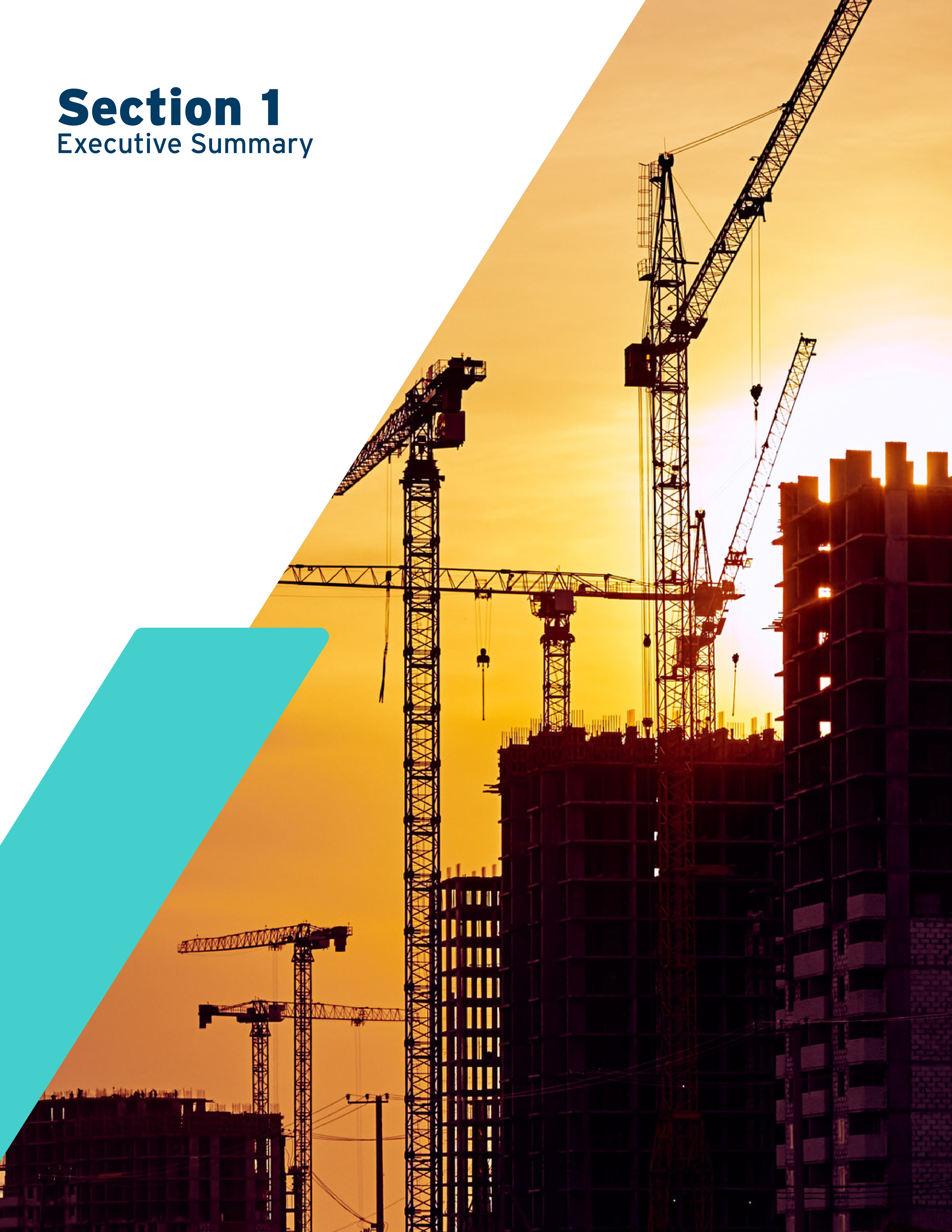
We thank Breakthrough Energy, LLC for its support in the production of this report.

About RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

Table of Contents

Section 1
Executive Summary



Executive Summary

Embodied Carbon: A Hidden Climate Challenge

Buildings account for at least 39% of energy-related global carbon emissions on an annual basis.[1] At least one-quarter of these emissions result from embodied carbon, or the carbon emissions associated with building materials and construction. The solutions for addressing embodied carbon in buildings have not been widely studied in the United States, leaving a significant knowledge gap for engineers, architects, contractors, policymakers, and building owners.

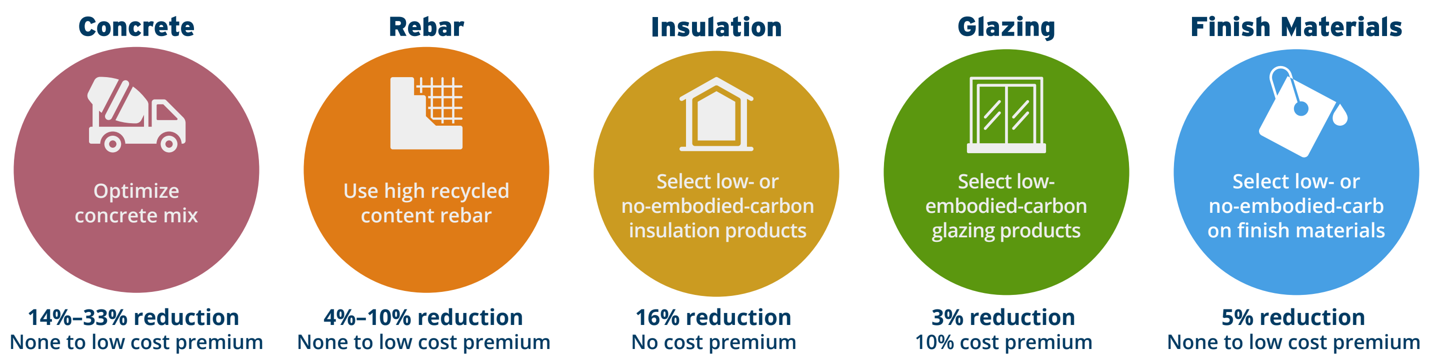
Embodied carbon can be reduced significantly at little to no additional up-front cost. The case studies showcased in this report show an embodied carbon savings potential of 19%–46% at cost premiums of less than 1%. Current practice indicates that we can achieve these reductions by specifying and substituting material alternatives with lower embodied carbon during the design and specification process. Far greater reductions are possible when a whole-building design approach is taken.

This report highlights the low-cost and no-cost solutions for reducing embodied carbon in buildings by studying three building types and considering design strategies that can reduce embodied carbon at any stage of a project's design and construction phases. The report quantifies the construction cost difference associated with low-embodied-carbon solutions and points to next-generation solutions that could drive even greater reductions.

Key Takeaways

- Up-front embodied carbon can be reduced by up to 46% in our case study building typologies with less than 1% cost premium.
- Optimizing ready-mix concrete design, choosing finish materials with low-embodied-carbon footprints, and considering low-embodied-carbon or carbon-sequestering insulation options are the most impactful no-cost measures for reducing embodied carbon.
- Designing for minimal material usage can reduce embodied carbon, lower up-front costs, and maintain a building's sound structure and aesthetics.
- Sourcing rebar and structural steel with higher recycled content, choosing low-embodied-carbon glazing products, and reducing structural system material needs are the most impactful low-cost measures.
- Currently emerging materials promise to significantly further reduce embodied impacts.

Exhibit 1 Top categories for reducing embodied carbon



What Is Embodied Carbon, and Why Is It Important?

Embodied carbon refers to the greenhouse gas emissions resulting from extracting, manufacturing, and installing materials and products over the life cycle of a building.[2] These emissions can also include the use phase and treatment of materials at the end of their useful lives (e.g., reuse, recycling, landfilling).

It's critical to understand which life-cycle stages are being considered in any study of embodied carbon. The most common characterizations are "cradle to gate" (covering material extraction, transportation, and manufacturing) and "cradle to grave" (which also includes the use phase and end-of-life considerations). End-of-life considerations are important for developing a holistic and consistent view of the environmental impacts that a material has through its disposal or reuse. However, end-of-life considerations are often omitted due to data scarcity, uncertainty about eventual treatment (will a product be landfilled, recycled, or reused?), or other unknowns.

This report will only consider the cradle-to-gate life-cycle stages, or up-front embodied carbon. These stages correspond to the A1–A3 life-cycle stages that are commonly used for life cycle analysis,[3] which refer to raw material supply, transport to the manufacturing site, and manufacturing. Up-front embodied carbon includes emissions related to the extraction, transportation (from extraction site to manufacturing site), and manufacture of materials. It does not include emissions related to transportation to the construction site, the construction or use phases, or end-of-life considerations. Therefore, the core conclusions and case study analysis in this report do not address end-of-life embodied carbon considerations, although the report does discuss end-of-life considerations at a high level.

Embodied carbon is critical for climate mitigation because it accounts for upward of 11% of global emissions[4] (up to 23% by some estimates),[5] but it has not been addressed at nearly the same scale as operational emissions (the emissions associated with energy consumption). As global construction continues to rise, and existing building operations become more efficient, embodied carbon will become an increasingly significant issue—accounting for approximately 50% of global building-sector emissions between now and 2050. This growing problem will account for a significant amount of our remaining carbon budget for keeping global warming below 1.5°C, and it needs to be addressed by policymakers and practitioners now to drive the most impact.[6]

The Time Value of Carbon

In the quest to reduce the emissions generated from building construction and operations, the most valuable opportunity for reducing carbon is at the beginning of a building's life. Embodied carbon is critical to mitigating global climate change, because most of these emissions typically occur up front, at the start of a building's life cycle. Architecture 2030 reports that "[u]nlike operational carbon emissions, which can be reduced over time with building energy efficiency renovations and the use of renewable energy, embodied carbon emissions are locked in place as soon as a building is built. It is critical that we get a handle on embodied carbon now if we hope to phase out fossil fuel emissions by the year 2050." Global construction is booming and is projected to continue to rise for decades.[7] It is therefore critical to reduce embodied carbon emissions as quickly as possible, because the emissions from construction today can remain in the atmosphere for hundreds of years. Reducing and avoiding both embodied and operating emissions is our best strategy for reducing the overall quantity of CO_2e in the atmosphere.

Lowering Embodied Carbon Can Drive Value

Embodied carbon reductions can deliver value beyond reducing carbon emissions.

Embodied carbon reductions can often **reduce project costs**. Reducing the amount of material needed in a project is one of the first steps that building designers can take to reduce embodied carbon. Procuring fewer materials will cost the owner and developer less money. Further, carbon-reduction strategies that reduce the cement content of many concrete mixes can also reduce cost, as cement is a driver of both cost and carbon for concrete. Projects that use mass timber for structural components also reduce project costs due to faster construction times with more modular components and simpler connections.

Low-embodied-carbon products also often **reduce energy consumption in extraction, manufacturing, and/or transportation.** Unless their process is driven by carbon-intensive chemical reactions, low-embodied-carbon products will, by nature, result in energy savings upstream of a material's end use. These savings typically result in operational cost savings for material manufacturers, which may be passed on to the end consumer.

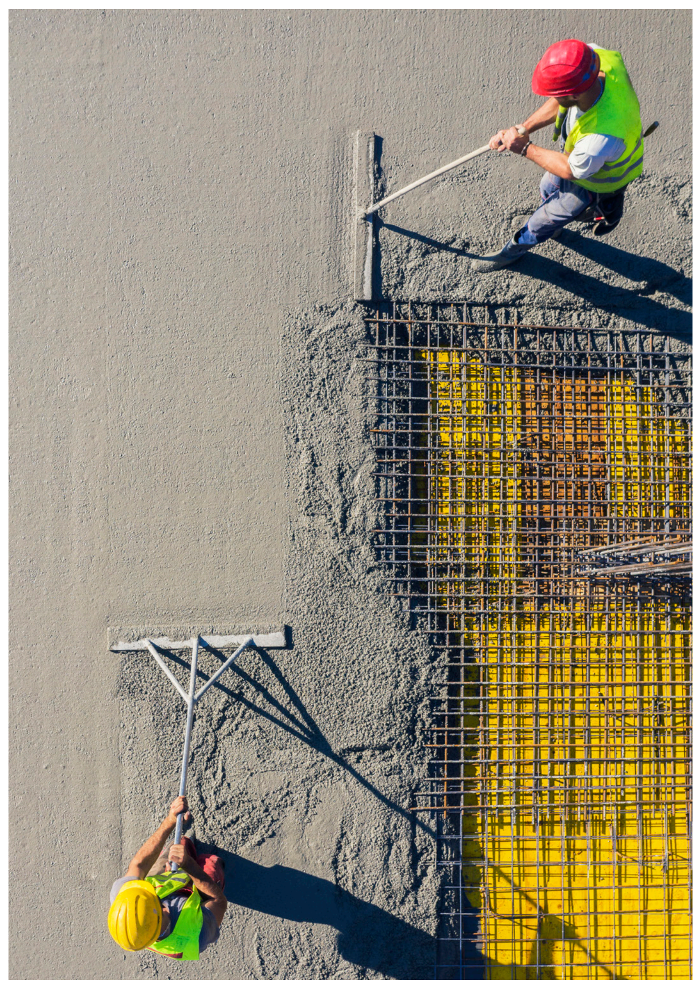
Building projects that reduce embodied carbon and/or include a whole-building life cycle assessment (WBLCA) **can help to meet green building certification requirements.** Certifications that incorporate embodied carbon include the Building Research Establishment Environmental Assessment Method (BREEAM), Excellence in Design for Greater Efficiencies (EDGE), LEED v4 from the U.S. Green Building Council, and both the Zero Carbon and Living Building Challenge certifications from the International Living Future Institute (ILFI).[8]

A low-embodied-carbon building design will also be **better prepared for future code or policy changes that incentivize or require low embodied carbon.** In the near term, these changes could take the form of a carbon tax, building code requirements, procurement policies (e.g., Buy Clean policies), development incentives, or other regulatory mechanisms. Although localities are unlikely to implement retroactive policies requiring low-embodied-carbon building design, building to a low-embodied-carbon standard will prepare developers, designers, and the construction industry for these likely future scenarios.

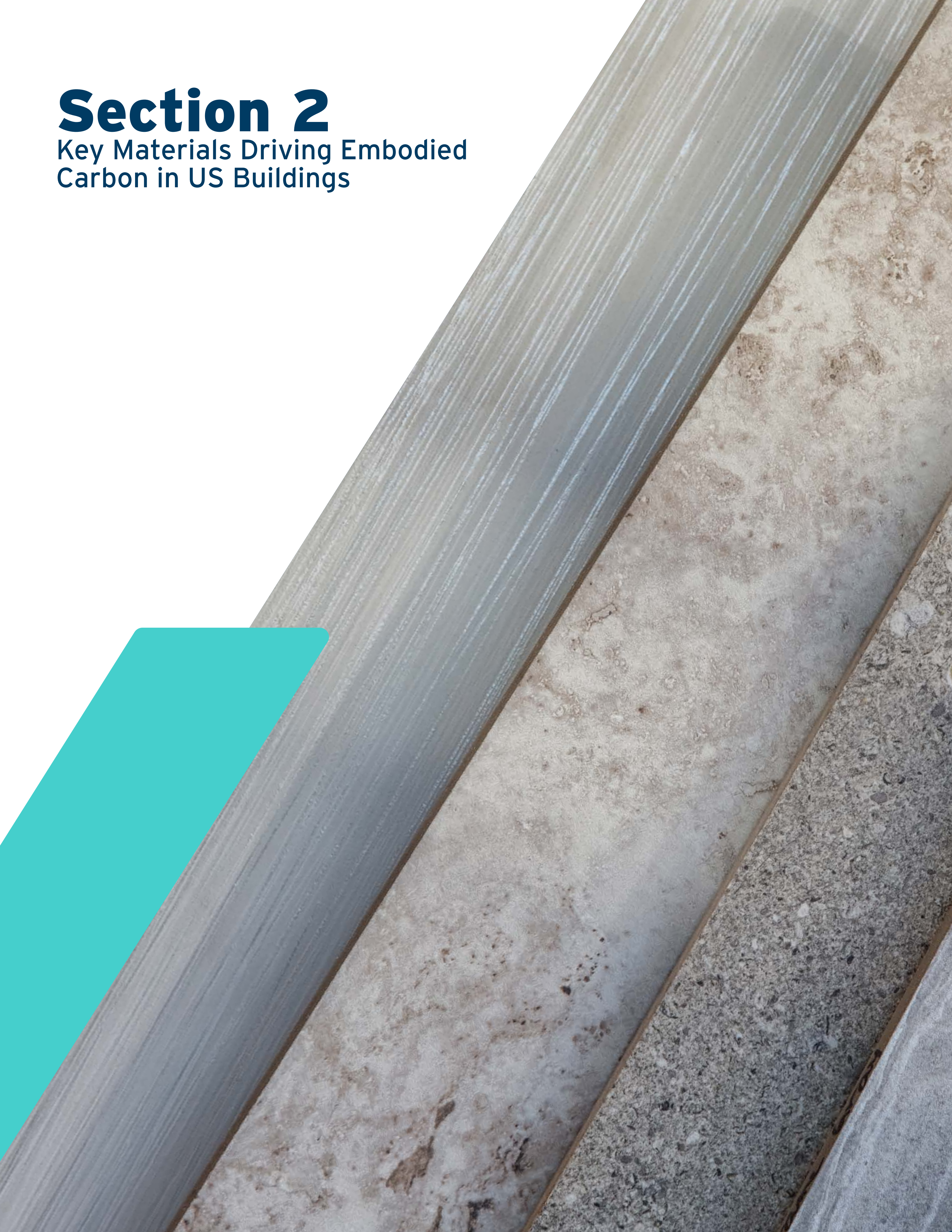
Finally, reducing emissions in the extraction, manufacturing, and transportation of low-embodied-carbon materials **improves air quality and public health** in communities located close to industrial centers. These health and environmental benefits are especially important for communities of color, including Black, Latinx, and Indigenous communities and people in areas with lower incomes, who are most directly impacted by industrial emissions through higher rates of asthma and other diseases.[9]

Setting the Stage

This report will lay out a framework for reducing embodied carbon in buildings and highlight the ways that the construction industry can cost-effectively reduce embodied carbon in some of the most prevalent building construction types in the United States today.



Section 2
Key Materials Driving Embodied Carbon in US Buildings



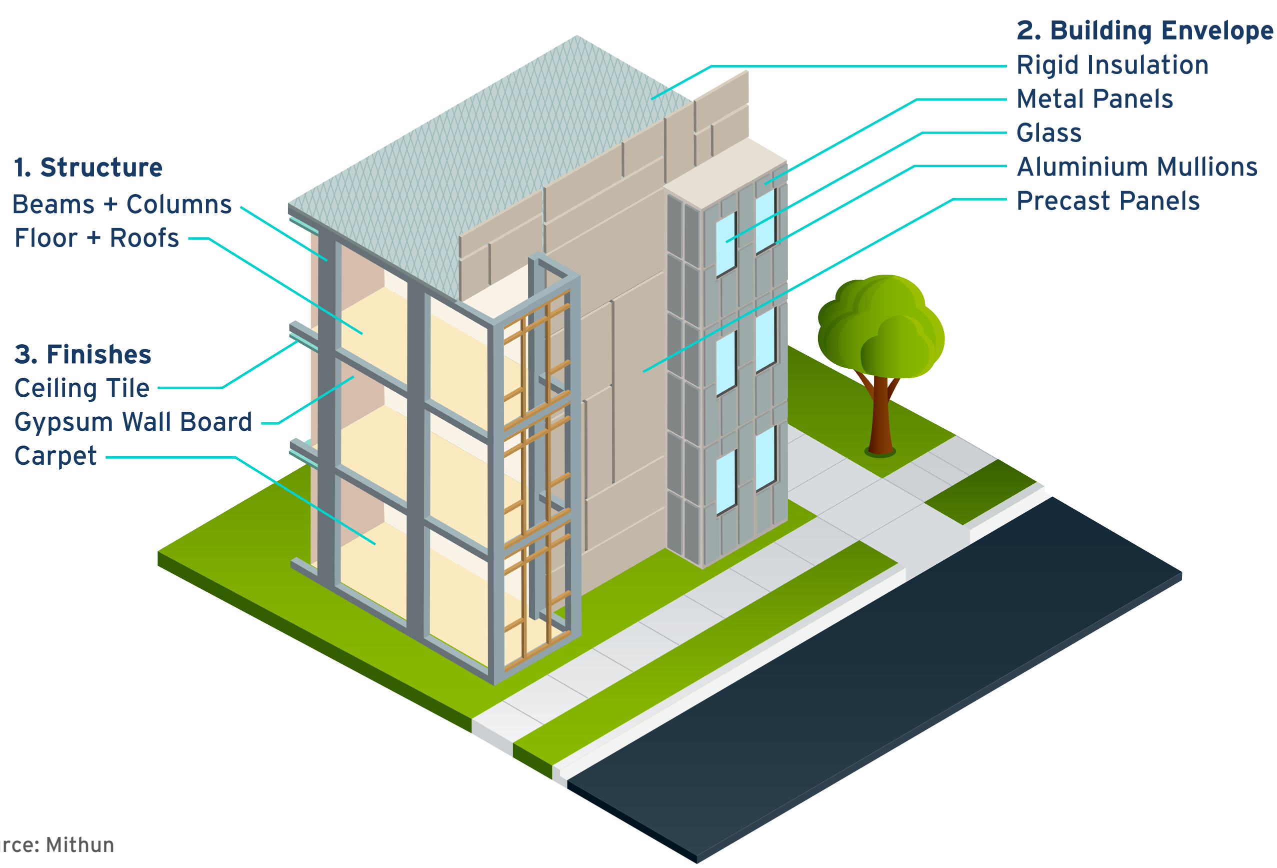
Key Materials Driving Embodied Carbon in US Buildings

Industry Overview

In order to tackle embodied carbon in buildings and initiate a sector-wide shift toward addressing the issue, we first need to understand the carbon impact of the industries driving embodied carbon emissions. WBLCAs show us that a building's structure and substructure typically constitute the largest source of its up-front embodied carbon, up to 80% depending on building type.[10] However, because of the relatively rapid renovation of building interiors associated with tenancy and turnover, the total embodied carbon from interiors can account for a similar amount of emissions over the lifetime of a building. In this report, we focus primarily on structural materials, metals (including steel and aluminum), cement, insulation, and timber. Each of these materials has a different embodied carbon content but is critical to our consideration of structural systems in this context.

We can better understand the carbon embodied in buildings by looking at these materials individually: cement and concrete, steel, timber, and insulation.

Exhibit 2 **Typical high-embodied-carbon structural elements, building envelope materials, and finish materials**



Source: Mithun

Cement and Concrete

Concrete is one of the most widely used materials in the construction industry and a primary source of embodied carbon in buildings. In fact, global use of concrete exceeds the consumption of any other material, aside from water.[11] Although each of concrete's constituent materials offer opportunities for reductions in embodied carbon, the high embodied carbon of concrete is primarily driven by the manufacture of one key ingredient—ordinary portland cement. Portland cement is the most common cementitious binder used in concrete mixtures in the United States, and the US cement industry is one of the largest contributors to US-borne emissions at 68.3 million metric tons (MMT) of CO_2e per year.[12]

While the layperson may use "cement" and "concrete" interchangeably, they are unique materials, and understanding the difference is key to the embodied carbon discussion. To build a building, construction professionals buy concrete (which contains cement), not the cement itself. Cement is used with water as a binder to adhere particles of sand and rock (aggregate) together to form concrete. The manufacture of cement tends to be centralized, and the mixing of cement into concrete is highly localized to minimize the expense of moving heavy aggregate.

Nearly 60% of CO_2 emissions from cement production come from chemical reactions that occur while producing clinker, an intermediary component of cement.[13] Since these emissions are the result of chemical reactions, they cannot be reduced or eliminated by increasing energy efficiency or by switching fuels. As such, one way to reduce the embodied carbon content of cement is by replacing a portion of the cement with supplementary cementitious materials (SCMs) such as fly ash and slag or by using a clinker-free alternative to portland cement.

However, SCMs are in high demand due to their ability to reduce the embodied carbon of cement and concrete,[14] and some SCMs are becoming less widely available. For instance, supply of fly ash, a by-product of coal power generation, is falling as coal is used less and less as a power generation source. High-quality aggregate can also reduce the amount of cement needed to produce concrete due to better adhesion and other properties. In some cases, it can even be worthwhile to import aggregate, as the improved strength properties can outweigh the carbon emissions associated with transportation.[15]

The remaining 40% of cement production emissions come from the burning of fossil fuels to heat the kilns required to produce clinker. The electrification of cement production, as well as the use of alternative fuels such as biomass and renewable energy, could help reduce emissions, but these strategies are currently in early stages of development and adoption. Researchers are exploring carbon capture techniques that would capture and store carbon emissions from the cement kilns as a potential solution, but these technologies are not market-ready. Because emissions associated with cement are so significant (almost 1 kg of CO_2 for each kg of cement manufactured), many researchers are working on emerging technologies to address this issue.[16] Today's technologies can help manufacturers make cement products with substantially less emissions at competitive prices, and emerging technologies may be able to produce zero-embodied-carbon cement, or even net carbon-negative products.[17]

The building construction industry's demand for concrete accounts for an estimated 51% of total portland cement produced in the United States.[18] Given its evident popularity in building construction, it's essential we address the high carbon intensity of this material. A forthcoming guide by RMI outlines how concrete ready-mix suppliers, developers, and contractors can leverage proven and cost-effective solutions to lower the embodied carbon of concrete.

Steel

The US steel industry is responsible for 104.6 MMT of CO_2 emissions annually, a contribution that makes up 2% of total US emissions.[19] Steel industry emissions have dropped by approximately 60% since 1990, largely due to technological improvements as well as increased recycling of scrap steel.[20] Even so, steel is a substantial source of embodied carbon emissions for the built environment that could theoretically be reduced to zero either through material substitution or through the production of cleaner steel.

In recent decades, the US steel industry has shifted away from the use of integrated steel mills and the primary use of blast oxygen furnaces, toward the use of more efficient electric arc furnaces (EAF), which use scrap steel as a primary input. Of all the US steel made in 2016, 70% was manufactured using efficient electric arc furnaces,[21] reflecting a switch that has indeed reduced the carbon footprint of steel. However, steel production remains an incredibly energy intensive process, and steel destined for the built environment is still responsible for 46 MMT of CO_2 emissions annually,[22] because EAFs are effectively as "clean" as their energy source.

The most straightforward way to reduce embodied carbon for structural steel today is to specify steel produced in facilities that operate using relatively low-emissions (or zero-emissions) energy sources such as hydroelectric, renewable hydrogen, solar, or wind.[23] Although zero-carbon steel may not be market-ready today, specifying steel produced in efficient factories will ensure less energy is used in production. In combination with cleaner electricity, this step can make a significant difference.[24]

Structural steel is the predominant structural framing material used in building construction, holding 46% of the market share for structural framing materials for nonresidential and multistory residential construction in 2017. Concrete and wood held 34% and 10% of the market share, respectively.[25] Steel reinforcing or "rebar," which is typically embedded in structural concrete, can also be a major use of steel.

Timber

Timber has been used in building construction for thousands of years and is still one of the most widely used building materials. In 2017, building construction accounted for 62% of wood product end use in the United States. Although conventionally used for construction of single-family houses and low-rise buildings, wood is attracting interest worldwide for the construction of taller buildings as wood products become an effective alternative to more carbon-intensive concrete and steel.

With the introduction of innovative design strategies and engineered wood products such as cross-laminated timber (CLT), wood is steadily becoming a more viable material option for low- and mid-rise buildings. The cost-effectiveness of wood products has helped drive interest as costs of steel and concrete rise, and wood products offer additional benefits for design flexibility, construction speed, and reduced environmental impact. Although CLT is not yet widely used in the United States, the wood-framed "podium" building design, which includes several stories of wood over one story of concrete, is gaining in popularity.

Timber could even be considered a net carbon-sequestering material, because the carbon sequestered during a tree's growth can surpass the carbon emitted during harvesting and manufacturing. However, this determination depends on the method of cultivation and harvest as well as the end-of-life considerations of the material. Considering wood as a carbon-sequestering material is a point of contention among industry experts, with debate largely revolving around varying forestry and harvesting practices and their effect on emissions. Nevertheless, timber is typically seen as a lower-carbon alternative to steel and concrete when used as a structural material.

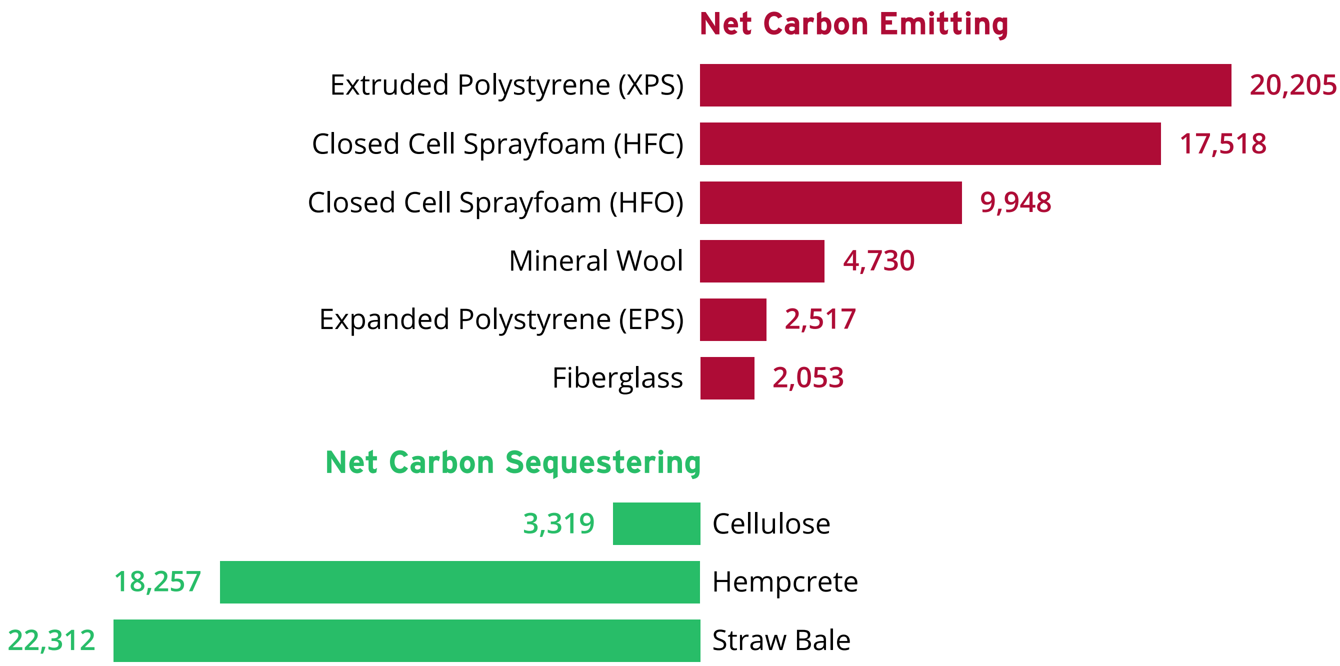
In order to fully understand the impact of timber materials, environmental assessments must first account for variation in forest management and harvesting practices, because differences in these practices produce great disparities in the amount of carbon sequestered. For example, the Forest Stewardship Council (FSC) certifies that wood products are responsibly and sustainably produced, and specifying FSC-certified products is a positive step toward managing low-carbon wood products.[26] However, FSC is not the only source of sustainably harvested wood, and groups that do not pursue certification can also have excellent forest management practices. When wood is not harvested sustainably, the resulting ecological destruction, increased soil degradation, and use of petroleum-based fertilizers can drastically increase the embodied carbon content of wood products.

As demand grows for wood products, it will be crucial to ensure this demand is met with sustainable forestry management practices. Otherwise, the broader use of timber as a building product could result in higher carbon emissions and less ecological diversity.[27]

Insulation

Insulation products are essential to creating operationally efficient buildings. Although they may represent a relatively small portion of an overall construction cost budget, they can be a significant contributor to a building's embodied carbon budget. This category of materials has products with a broad range of embodied carbon impacts, from carbon-intensive, petrochemical-based contributors to carbon-negative options. For example, rigid or spray foam products have the greatest associated emissions, whereas biological-based materials (such as cellulose and cotton products) can contribute very little embodied carbon or even be considered as net carbon-sequestering products. The insulative capacity of a product, measured as thermal resistance, or R-value, varies between material type, with high values indicating higher performing insulation. Biological-based materials tend to have lower R-values than carbon-intensive materials and would require a thicker application of the product to achieve an equivalent level of performance. Exhibit 3 demonstrates the relative up-front embodied carbon emissions associated with various insulation materials.

Exhibit 3 Embodied carbon of insulation materials (kg CO_2e)



Note: The amount of CO_2e is based on R-20 at 234 m^2.

Source: Chris Magwood, *Opportunities for CO_2 Capture and Storage in Building Materials*, 10.13140/RG.2.2.32171.39208, 2019.

Moving Forward

Although embodied carbon reduction strategies exist today, there are several significant barriers to achieving these reductions. Perceptions of high cost, along with industry resistance to change, have stifled progress. Misinformation and low product availability have contributed to misconceptions that low-embodied-carbon products are more complicated to use or procure, or that they are inferior in strength or quality. Additionally, most industry decision makers and developers remain unaware of the embodied carbon discussion and therefore do not know to request these products to begin with, or they might not be aware of tools that can help them identify and track their project's emissions. Structural engineers, architects, and other specifiers could significantly reduce embodied carbon in new construction projects at little to no additional cost by using the tools and resources available to them today, detailed in Section 3.

There are many more materials and construction methods that can deliver substantial carbon reductions in buildings beyond what is covered in this report. The processes, solutions, and case studies offered in the following sections can help developers, designers, and construction professionals achieve low embodied carbon in buildings based on today's best practices.

Section 3
Proven Solutions and Strategies to Reduce Embodied Carbon

Proven Solutions and Strategies to Reduce Embodied Carbon

Building a common understanding of solutions and strategies to reduce embodied carbon in buildings is a critical first step to testing the economic value and technical potential of low-embodied-carbon construction.

Characterizing Low-Embodied-Carbon Solutions

Today, there are many solutions that can be leveraged to limit embodied carbon in new buildings. The totality of low-embodied-carbon solutions includes a long list of offerings that span a wide range of complexity.

Most simply, low-embodied-carbon solutions for buildings can be broken down into three main categories: **whole-building design, one-for-one material substitution,** and **specification**. In general, whole-building design solutions can drive the greatest embodied carbon savings. However, material substitution and specification can also result in substantial embodied carbon savings, especially when these solutions target carbon-intensive materials such as concrete and steel. Furthermore, these categories are not mutually exclusive—they can be combined or performed in parallel to drive deeper embodied carbon savings.

The examples corresponding with each strategy barely scratch the surface of possible low-embodied-carbon solutions.

As the world becomes more fluent in low-embodied-carbon construction, new design strategies may prove themselves more impactful, some materials may be produced more efficiently, and architectural styles may shift—all changing the calculation around designing for low embodied carbon.

Whole-building design

Initial decisions that affect the fundamental design of a building to reduce embodied carbon while meeting the functional requirements of the project.

These strategies include adaptive reuse of an existing building, reducing the overall square footage of a project, using more efficient structural systems or alternative building techniques, using prefabricated systems or components, and designing to minimize waste.

Example
Minimizing the overall quantity of material used in a building, especially high-embodied-carbon materials such as concrete, steel, and petrochemical-based insulation products, can significantly reduce the overall embodied carbon of a project.

Impact
Designing for additional levels of structural efficiency and material savings can yield "compounding efficiency," where lighter structures reduce material quantities as well as requirements for foundations. This can directly result in material cost savings.

Key Considerations
Tracking embodied carbon in terms of kilograms of CO2e per square foot is key to quantifying the benefit of material quantity reductions. Structural engineers often design for efficiency automatically based on economics, but because they work within the framing scheme shared by the architect, engineers and architects need a collaborative approach to achieve deeper savings.

One-for-one material substitution

Direct replacement of one material with another that will meet the functional requirements of the original design while having a lower global warming potential (GWP).

Example
Choosing cellulose as an insulating material in place of a petroleum-based insulation (e.g., expanded polystyrene) can achieve the same functional need (insulation) while dramatically reducing the embodied carbon of the overall project.

Impact
In some cases, insulation products can lead to near-zero or net negative (sequestering) carbon emissions.

Key Considerations
When considering two materials, it's important to consider their functional performance. For insulation products, this includes their thermal properties (e.g., R-value) as well as their form factors (e.g., blown product, rigid board, batt) and other performance qualities (whether they also provide an air barrier, resist fire, repel pests, etc.).

Specification

Establishing a value or limit for a material characteristic that will dramatically reduce embodied carbon content.

Example

A designer can specify a desired percent reduction of GWP in a given concrete mix. To meet this demand, the manufacturer could incorporate changes to the concrete mix design that reduces embodied carbon while meeting the necessary strength requirements. These changes may include lowering the ratio of portland cement, incorporating supplementary cementitious materials (SCMs), or using aggregate that will result in lower total embodied carbon.

Impact

Cement often drives the embodied carbon of a given concrete mix, and lowering its content will reduce the carbon impact of the project.

Key Considerations

Reducing portland cement content may lead to notable changes in process, such as longer cure times for a given cement mix. Note that for a given material choice, the design team can use open-source tools such as EC3 or other databases (see page 19 for more information on these resources) to identify the lower-carbon, cost-comparable option for their project. Some suppliers may not have environmental product declaration (EPD) data displaying the embodied carbon content of the material to prove it has a lower embodied carbon content than standard products. These data limitations are expected to improve as demand grows for low-embodied-carbon materials.

Applying Low-Embodied-Carbon Solutions to the Design and Construction Process

The most effective path to reducing cost and carbon on a building construction or renovation project is to set embodied carbon goals and perform analyses early in the design process. The initial prioritization of embodied carbon will enable the design team to consider whole-building design solutions, which can yield substantial reductions in embodied carbon. It's important that design solutions are established early in the process because it becomes more difficult and expensive to make fundamental changes as the project becomes more definite.

Other interventions, such as material replacement and specification, naturally occur later in the design process when the project is more defined. Substituting and specifying low-embodied-carbon materials alone can have significant impact on the embodied carbon of a construction or renovation project.

Strategies to reduce embodied carbon exist for every stage of the design process, from predesign and site selection through occupancy (see Exhibit 4). Implementing these strategies falls under the responsibility of numerous stakeholders and requires a level of collaboration beyond standard practice. To foster the strong working relationships needed to execute these strategies, it is critical that the project owner bring together the architect, engineer, energy or sustainability consultant, contractor (if possible), and other major stakeholders at the outset of a project to establish roles and responsibilities and set frequent check-ins throughout the design and construction process.

Exhibit 4

Strategies to reduce embodied carbon throughout the design and development process

Primary Roles

Architect · Contractor · Manufacturer · Owner · Structural Engineer · Geotechnical Engineer · Landscape Architect

Whole-Building Design

Material Substitution

Specification & Procurement

1 Predesign & Site Selection	Owner, Architect	Consider reusing an existing building before deciding to design a new building.
	Geotechnical Engineer, Structural Engineer, Architect	Assess soil type and determine options for the building's foundation. Some types of foundations use greater quantities of materials than others.
	Architect	Consider salvaging or reusing materials from a building that is to be deconstructed.
	Owner, Architect	Set an embodied carbon budget for the project based on LCA calculations for similar buildings or case studies.
2 Conceptual & Schematic Design	Structural Engineer, Architect	Ensure structural systems are compact, efficient, and not oversized.
	Architect	Design flexible and efficient spaces that allow for long-term changes in use.
	Architect	Design for future disassembly and reuse.
	Structural Engineer, Landscape Architect, Architect	Consider the embodied carbon trade-offs related to architectural design decisions such as massing, envelope systems, foundations, and landscaping.
	Architect	Conduct an initial whole-building LCA (WBLCA) or perform an LCA for "hot spot" materials or assemblies with higher carbon intensities.
	Architect	Select building systems and assemblies that minimize embodied carbon.
	Architect	Assess availability of local reused and locally sourced materials.
3 Design Development & Construction Documents	Architect	Specify material characteristics that result in low embodied carbon.
	Architect	Substitute like-for-like materials that offer lower global warming potential
	Structural Engineer, Architect	Consider the embodied carbon trade-offs related to architectural and structural refinements and changes.
	Architect	Update WBLCA as needed.
4 Bidding & Procurement	Architect	Incorporate clear embodied carbon goals in all procurement language and set building system or material-specific goals.
	Architect	Include requirements for product substitutions in the specifications.
	Manufacturer, Contractor, Architect	Request embodied carbon data, including EPDs, from all vendors.
	Manufacturer, Contractor, Architect	Include previous work, experience, and proposed solutions that address embodied carbon in any procurement selection criteria.
	Contractor, Architect	Design a subcontractor selection process that incentivizes bidders to offer lower-embodied-carbon materials and methods.
5 Construction	Contractor, Architect	Establish clear guidelines and targets to reduce construction waste.
	Contractor, Architect	Hold contractors accountable for delivering low-embodied-carbon design committed to in previous phases.
	Owner	Consider offering monetary performance bonuses for additional embodied carbon reductions identified and executed during the construction process.
	Architect	Document the as-built embodied carbon content of the building and publish the data.
	Architect	Update WBLCA as needed.
6 Occupancy: Maintenance, Renovations & Tenant Fit-Outs	Owner, Contractor, Architect	Debrief and apply lessons learned to future projects.
	Owner, Contractor, Architect	Establish embodied carbon reduction targets for future renovations and tenant fit-outs.

Source: Partially adapted from *Embodied Carbon Quick Guide: A Quick Reference Guide for Teams to Reduce their Project's Embodied Carbon*, International Living Future Institute, 2020.

Current Tools for Implementation

A number of open-source and subscription-based tools are available to support low-embodied-carbon design and construction strategies. The following tools can be used to assess and reduce the environmental impact of projects:

- The **Athena Impact Estimator for Buildings** is a free software tool for conducting a comprehensive life cycle assessment of buildings. It draws on an embedded database of regionally specific material life-cycle data. The tool allows for side-by-side comparisons providing clear visibility into the impacts of various design choices.
- **The Carbon Smart Materials Palette** is an Architecture 2030 project that provides "attribute-based design and material specification guidance" intended to connect designers and specifiers with information about key materials and actionable information about how to reduce embodied carbon during the design and construction process.[28]
- The **Embodied Carbon in Construction Calculator (EC3)** is an open-source database that houses thousands of digitized, third-party verified Environmental Product Declarations (EPDs). This tool is most useful in providing transparency of information and comparing the carbon impact of different product options across similar material types. EC3 also allows users to compare the up-front (A1–A3) embodied carbon impacts of different building materials for a given project, but it is not intended as a WBLCA tool.
- **One Click LCA** is a subscription-based software product that integrates with building information modeling (BIM) and an extensive database of material EPDs to produce a life cycle assessment in any design stage of a project.
- **Tally** is an application that allows architects and engineers to perform highly detailed WBLCAs of projects directly within the Revit design platform.

Redevelopment and Reuse

When embarking on a building project, the first consideration should be whether new construction is needed at all.[29] The embodied carbon impact of redeveloping an existing structure is 50% to 75% lower than the impact of constructing a new building.[30] By repurposing existing assets, both cost and carbon emissions associated with new building materials are avoided. Even if the foundation and structure are the only elements retained, their reuse will have a significant impact on the embodied carbon of the project, because these components generally account for a majority of a building's carbon footprint.

If redeveloping an existing building is not a viable option, consider incorporating recycled materials into the design wherever possible. It is also important to design with the end of the building's life in mind, ensuring the systems can be easily deconstructed and reused or that the building can be easily reconfigured to fill another use.

The following section presents case studies that apply a number of low-embodied-carbon solutions to achieve substantial embodied carbon reductions at less than 1% additional cost.

Section 4

Case Studies in the Economics of Low-Embodied-Carbon Buildings

Case Studies in the Economics of Low-Embodied-Carbon Buildings

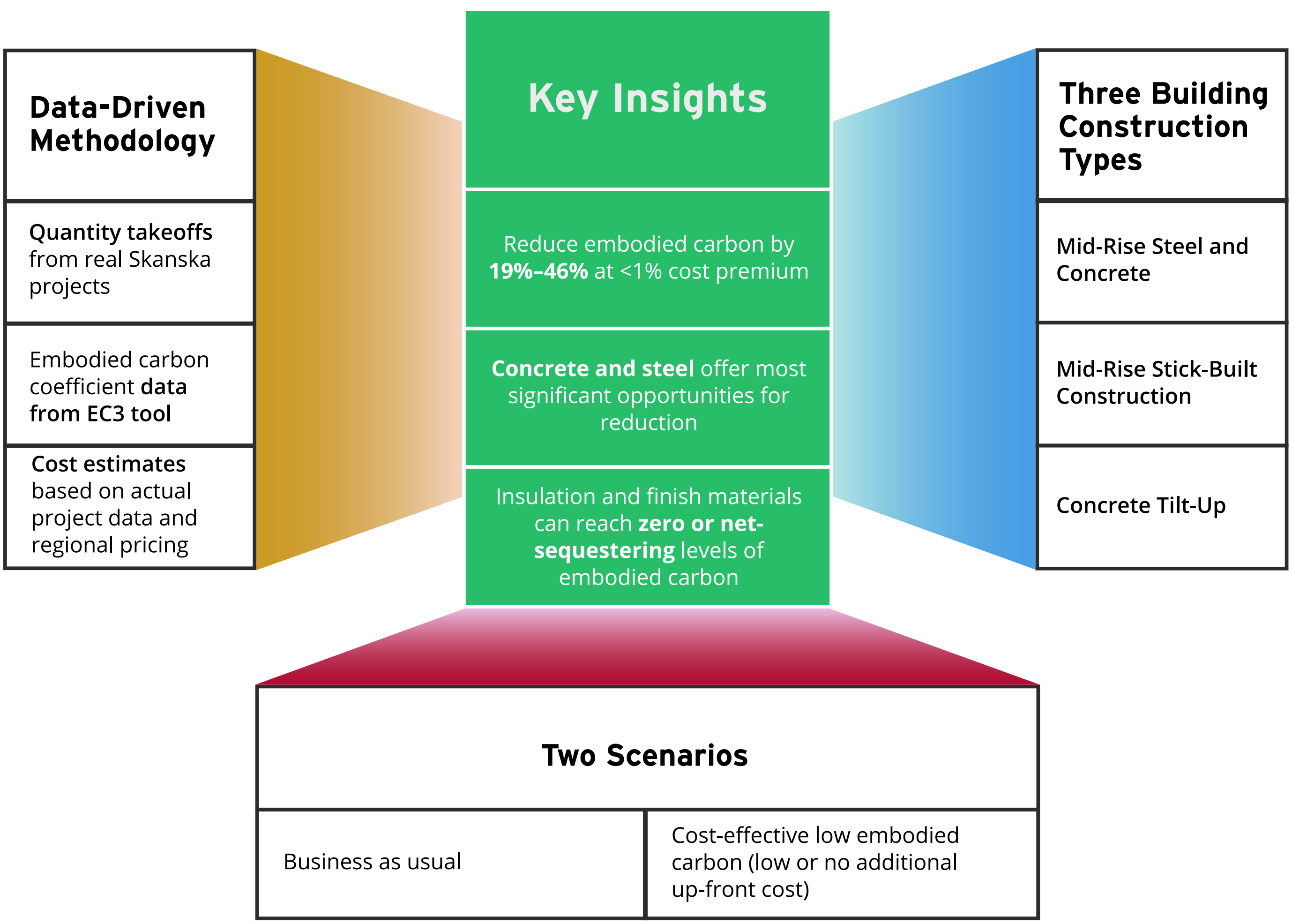
Overview

One of the core objectives of the report is to answer the question: How much can we reduce embodied carbon in new buildings at no additional cost?

In short, this study shows that embodied carbon can be reduced by 19%–46% in mid-rise commercial office, multifamily, and tilt-up-style buildings by leveraging low- and no-cost measures. Together, these measures increased overall project costs by less than 1%, which is within the margin of error for most construction project budgets.

Skanska, one of the world's leading sustainable construction firms, provided cost data from three actual projects in the Pacific Northwest and conducted an analysis under the guidance of RMI to generate the results of this study.

Exhibit 5 Methodology and assumptions for the report's case study modeling exercises



Methodology

Skanska and RMI chose the three building construction types included in this study based on the most significant building use types that exist in the United States today by gross square footage.[31] This includes buildings with a steel-reinforced concrete slab and steel and concrete above grade (case study 1), buildings with a steel-reinforced concrete slab and traditional timber framing above grade (case study 2), and buildings with tilt-up construction (case study 3). Case studies 1 and 2 are representative of traditional mid-rise office and multifamily residential buildings, whereas case study 3 represents a construction methodology commonly used for big-box retail, warehouses, and data centers.

Skanska chose three representative buildings of these construction types from its recent construction portfolio. As a full-service design, cost estimation, and construction firm, Skanska was able to produce quantity takeoffs and cost estimates for each of these buildings. Skanska combined the quantity takeoff information for these three projects with environmental performance data from the Embodied Carbon in Construction Calculator (EC3) tool to develop a high-level estimate of the up-front embodied carbon associated with constructing the structural systems, insulation, glazing, and interior finish materials within each existing building design. The original cost and quantity takeoff information, combined with the up-front (cradle-to-gate, or A1–A3) embodied carbon data from EC3, established our baseline case.

Skanska then modified each of these baseline buildings to develop a "cost-effective embodied carbon reduction" scenario. The main methodology for this scenario was to select materials that represent the 80th percentile of carbon dioxide equivalent established in available environmental product declarations (EPDs) for the chosen material. EPDs are essentially independently verified product labels that approximate embodied carbon and other environmental impacts. Skanska's methodology focused on one-for-one material substitution and specification strategies, as performing whole-building

design changes would be difficult to reflect in the models. Then, Skanska performed a cost analysis to either affirm that the chosen material would have no attributable cost increase, or to calculate a cost premium for the chosen material. The materials that were chosen for this "cost-effective" scenario were not to increase total project cost by more than 1%.

RMI and Skanska also intended to include additional embodied carbon reduction measures that would drive deeper whole-building embodied carbon reductions. Many of the measures in this category are under development or not widely available in the United States; others could not be accurately costed. As a result, these advanced material solutions are not included in the scenarios below but are addressed qualitatively in section 5.

Limitations of This Study

Ideally, this study would incorporate data from thousands of projects across the United States. Such a sample would provide a diversity of cost estimates from construction firms, an understanding of regional variation in pricing and availability, and a statistically significant sample of costs and quantity takeoffs.

The data and the assertions made in this study are based on the scenarios that RMI and Skanska studied. However, they cannot be generalized to all building typologies, or across every building project, because they were not drawn from a statistically significant sample, nor are these construction use types perfectly representative of their respective construction types.

Additionally, the case studies only address up-front embodied carbon, which considers life-cycle stages A1–A3 (extraction, manufacturing, and transportation between those processes), or a cradle-to-gate system boundary. The case studies do not consider the emissions related to construction, use, or the end of a product's life (including any of the considerations in life-cycle stages A4–A5, B, C, or D).

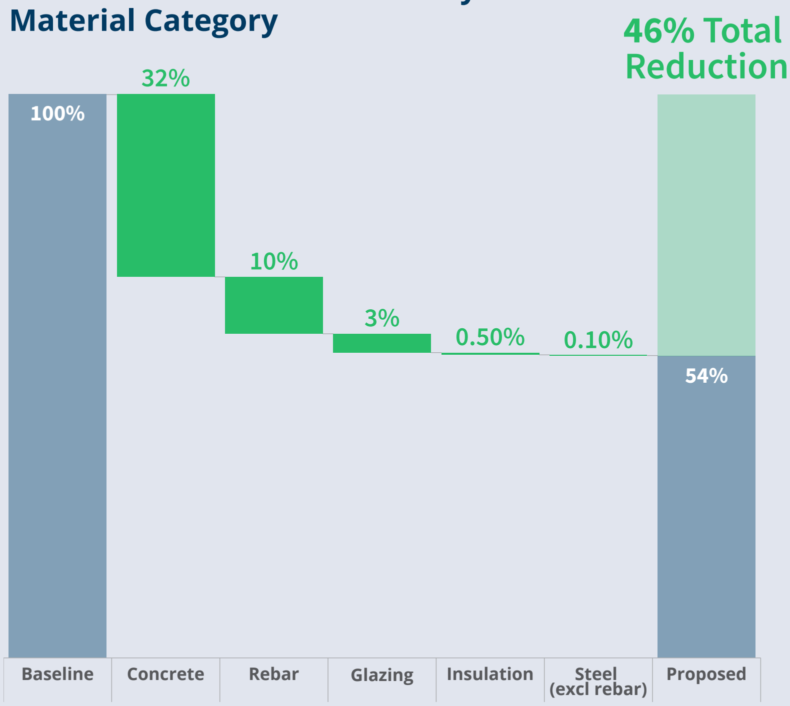
Finally, this study does not include any whole-building design strategy changes. Although these strategies (e.g., redesigning a building to use different or fewer structural materials) can often achieve significant reductions at low cost, the scope of this project limited our analysis to use of the EC3 tool. EC3 can readily make specification and one-for-one material substitution comparisons, but it does not have the capability to inform whole-building design changes.

The following case studies detail our key findings for each construction use type.

Case Study 1: Mid-Rise Concrete and Steel Construction

In a five-story, 200,000 ft^2, mixed-use office building with a **steel-reinforced concrete slab and steel and concrete above-grade** construction, we identified a potential **46% reduction** in up-front embodied carbon by focusing on a wide array of building components. The cost premium for this reduction in embodied carbon is **less than 0.5%** of the overall project cost.

Embodied Carbon Reduction by Material Category



Up-front embodied carbon reduction from baseline

46%

Cost premium of low-embodied-carbon measures

< 0.5%
Of Total Budget

CO_2e reduced
(metric tons)

2,228

Building components in scope

Structural systems
Glazing
Roofing
Interior wall materials (unfinished)
Insulation

Top no-cost measures *(measures that do not add to total project cost)*

Specify lower-embodied-carbon products:
- Ready-mix concrete: optimize ready-mix supplier award selection, procure lower cement mix designs, and allow for 56-day strength obtainment
- Metal decking
- Roofing

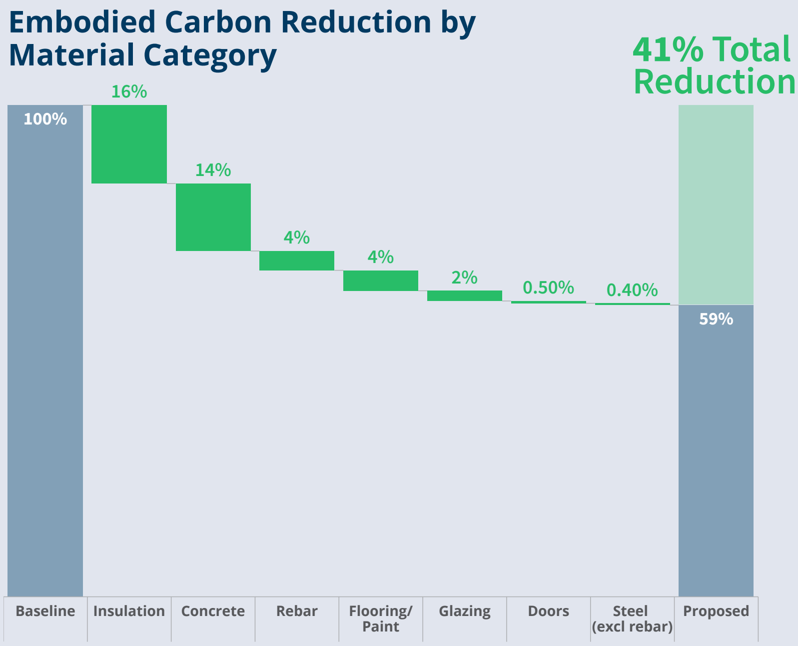
One-for-one material substitution:
- Gypsum sheathing
- Insulation materials: procure lower-embodied-carbon insulation products such as polyiso or mineral wool batt in lieu of materials with higher GWPs, such as XPS

Top low-cost measures *(measures that have a small cost premium associated with lower-embodied-carbon alternatives)*

Specify lower-embodied-carbon products:
- Glazing: procure lower-embodied-carbon glazing products
- Structural steel and rebar: strategically procure steel from mills that incorporate high recycled content steel, electric arc furnace technology, and clean electrical supply

Case Study 2: Mid-Rise Stick-Built Construction

In a six-story, 125,000 ft^2, mixed-use multifamily building with **lumber framing above a steel-reinforced concrete slab**, we identified a potential **41% reduction** in up-front embodied carbon by focusing on a wide array of building components. The cost premium for this reduction in embodied carbon is **less than 0.5%** of the overall project cost, in line with the results of case study 1.



Up-front embodied carbon reduction from baseline

41%

Cost premium of low-embodied-carbon measures

< 0.5%
Of Total Budget

CO_2e reduced
(metric tons)

1,482

Building components in scope

Structural systems
Glazing
Roofing
Interior wall materials
Insulation
Wall/floor finish materials

Top no-cost measures *(measures that do not add to total project cost)*

Specify lower-embodied-carbon products:
- Ready-mix concrete: optimize ready mix supplier award selection, procure lower cement mix designs for foundation and basement, and allow for 56-day strength obtainment
- Moisture barrier: choose lower-embodied-carbon products
- Wood: procure locally produced and sustainably sourced wood products, including structural wood and sheathing products

One-for-one material substitution:
- Gypsum sheathing: procure lower-embodied-carbon gypsum sheathing products
- Insulation materials: procure lower-embodied-carbon insulation products such as polyiso or mineral wool batt in lieu of materials with higher global warming potential (GWP), such as XPS
- Interior and fit-out: choose interior finish and fit-out products with lower embodied carbon content, including interior and exterior doors, carpet tiles, paints, and interior walls

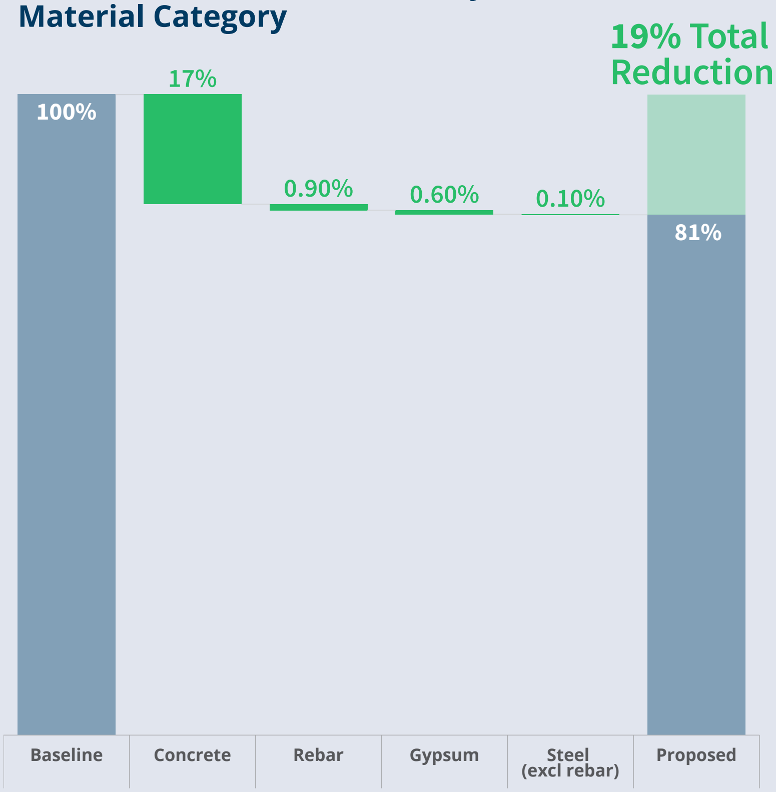
Top low-cost measures *(measures that have a small cost premium associated with lower-embodied-carbon alternatives)*

Specify lower-embodied-carbon products:
- Glazing: procure lower-embodied-carbon glazing products
- Structural steel and rebar: strategically procure steel from mills that incorporate high recycled content steel, electric arc furnace technology, and clean electrical supply

Case Study 3: Tilt-Up Construction

In a 360,000 ft^2 **tilt-up concrete warehouse**, we identified a potential **19% reduction** in up-front embodied carbon by focusing on shell and core materials only. The cost premium for this reduction in embodied carbon is **less than 1%** of the project cost—a slightly higher premium as compared with case studies 1 and 2 but still within the margin of error for most construction projects.

Embodied Carbon Reduction by Material Category



Up-front embodied carbon reduction from baseline

19%

Cost premium of low-embodied-carbon measures

< 1%
Of Total Budget

CO_2e reduced (metric tons)

2,501

Building components in scope

Shell and core materials only:

Concrete	Metal panels
Rebar	Roofing
Structural steel	Gypsum sheathing
Metal decking	Rigid insulation
Glazing	

Top no-cost measures *(measures that do not add to total project cost)*

Specify lower-embodied-carbon products:
- Insulation materials: procure lower-embodied-carbon insulation products such as polyiso or mineral wool batt in lieu of materials with higher GWP, such as XPS
- Ready-mix concrete: optimize ready mix supplier award selection, procure lower cement mix designs for foundation and basement, and allow for 56-day strength obtainment

Top low-cost measures *(measures that have a small cost premium associated with lower-embodied-carbon alternatives)*

Specify lower-embodied-carbon products:
- Glazing: procure lower-embodied-carbon glazing products
- Structural steel and rebar: strategically procure steel from mills that incorporate high recycled content steel, electric arc furnace technology, and clean electrical supply

Interior Fit-Out

Although it is commonly understood that the structure of a typical building accounts for the majority of the building's up-front embodied carbon footprint, examining the recurring cycle of renovation over a building's life reveals the importance of interior finish materials.

In some cases, the cumulative impacts of multiple renovation cycles can surpass the up-front embodied carbon accumulated during a building's construction.[32] A recent report from architecture and design firm Hawley Peterson Snyder conservatively estimated that building interiors are renovated or replaced on a 15-year cycle, adding to the building's total embodied carbon each time.[33] In cities with high frequency of tenant improvements, this cycle could be much shorter. Building typology also plays a key factor in the relative impact of interior fit-outs. For instance, commercial and residential buildings are renovated at higher frequencies than other buildings, leading to higher cumulative impacts of embodied carbon.

In a 2019 study, the Carbon Leadership Forum measured the impacts of initial construction combined with mechanical, electrical, and plumbing (MEP) and tenant improvements (TI), recurring at intervals of 15 years. The results indicated that when replacements of MEP and TI accumulate over a 60-year building life span, the combined impacts exceed the initial construction impacts in certain cases.[34]

Materials used for interior fit-outs are often made by companies with highly variable product lines, so providing EPDs for each product can be time- and cost-prohibitive.[35] In a study conducted by the Carbon Leadership Forum, the material categories that were found to carry the highest global warming potential (GWP) in interior fit-outs, such as aluminum-framed storefronts, HVAC components, interior partitions, and wood flooring and underlayment, lacked essential LCA data.[36] These current data limitations are expected to improve as demand grows for low-embodied-carbon fit-out materials. Design practitioners should reduce the quantity of high-embodied-carbon materials if a low-impact alternative is not available in their region.

Further Opportunities to Reduce Embodied Carbon in Case Study Buildings

There are several embodied carbon reduction opportunities that go beyond the specification and one-for-one material substitution opportunities included in our analysis. These include:

- Interior finish and fit-out reductions,[i] including:
  - Substituting traditional drywall with lightweight or alternative (plant-based) drywall materials
  - Substituting low-embodied-carbon carpet tiles made from alternative materials
  - Specifying lower-embodied-carbon ceiling tiles and paint products
- Replacing or redesigning cladding and structural elements,[ii] such as:
  - Replacing metal decking or light-gauge steel wall panels with wood-based alternatives
  - Redesigning entire structural systems to leverage lighter-weight materials (such as wood) and recalculating the size and material content of slabs and other foundational structural elements
- Whole-building design considerations,[iii] including:
  - Adaptive reuse of existing buildings
  - Reducing floor area for greater occupant density or more efficient use of floor space

Discussion

These results lead us to a few powerful observations. Even though the strategies employed do not include comprehensive whole-building design strategies, they still yield a 19%–46% reduction in up-front embodied carbon through specification and material substitution measures. Given that these conclusions are based on three case studies in the Pacific Northwest, we can note them as strong anecdotal evidence, rather than broadly applicable conclusions.

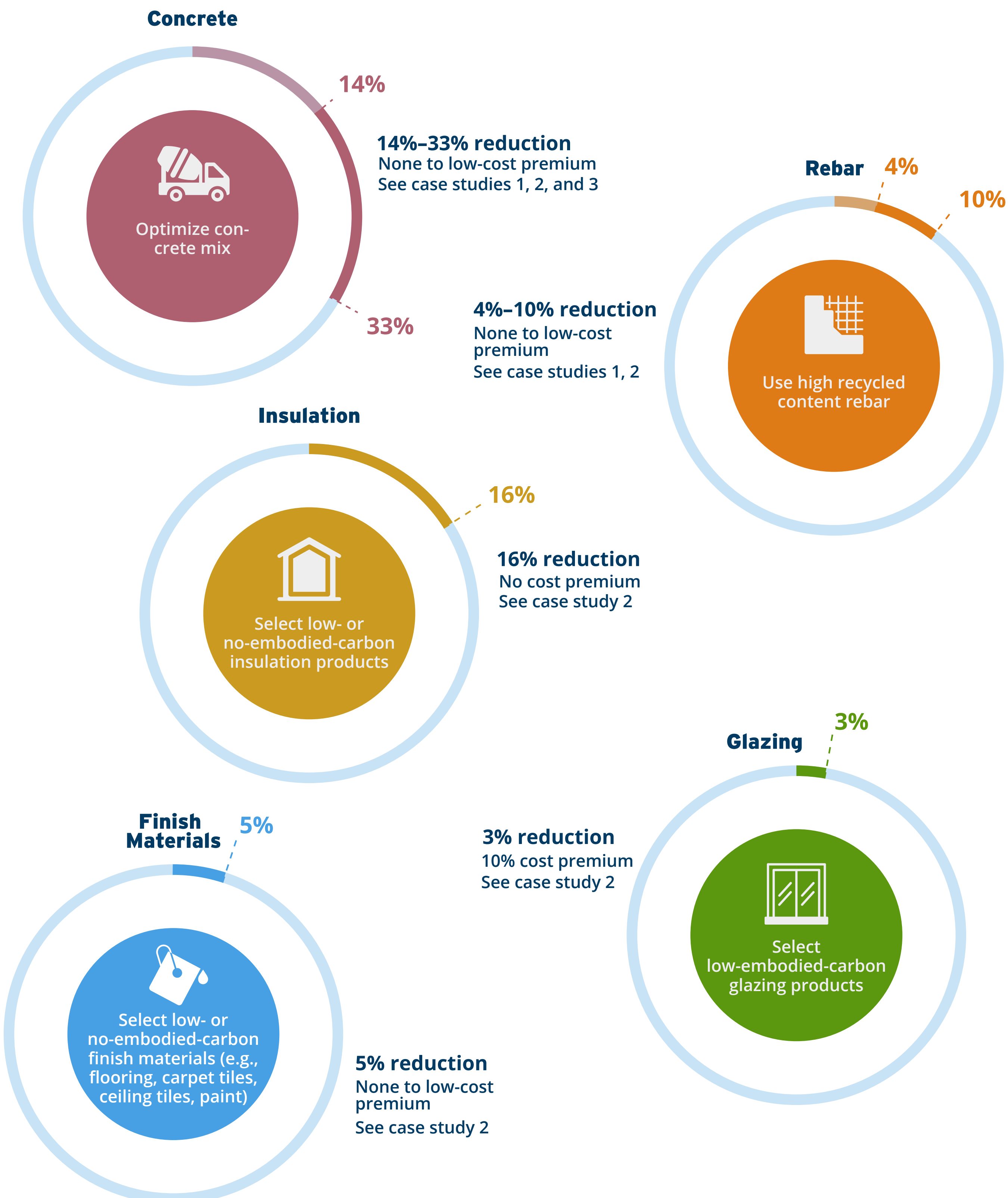
We had hoped to draw stronger conclusions from these case studies about the cost, carbon, and material impacts of substituting more structural steel and concrete with wood, but because of the limits of our study (namely the fact that we were not able to redesign building structural systems), we were unable to draw such conclusions.

Key Findings

1. **Optimizing the ready-mix concrete design can lead to significant embodied carbon reductions at no cost.** Ready-mix concrete design optimization yielded a 14%–33% reduction in project-wide embodied carbon across the three scenarios when compared with the baseline buildings. Depending on the changes to mix design, this measure carries either no cost or a possible cost reduction.
2. **Rebar with high recycled content coming from efficient mills, electric arc furnaces, and clean electrical grids can have dramatic impacts at a small cost premium.** Rebar contributed up to 10% of total project embodied carbon content in the case study 1 and 2 buildings. For these projects in the Pacific Northwest, the up-front embodied carbon of rebar can be cut in half with minimal impact to the overall project budget, although rebar with high recycled material content may not be available at a low cost premium in other regions.
3. **Insulation material selection can drive project-level embodied carbon**, but it depends on the baseline material types selected and the quantity of insulation. Case study 2 showed insulation as approximately 20% of the building's baseline embodied carbon content, leveraging a traditional foam-based insulation board. Rigid and spray foam insulation products utilizing HFO or other low-GWP based foaming agents can reduce embodied carbon impacts significantly. Several emerging products also leverage plant-based materials, which have the potential to store more carbon than is emitted in their production.
4. **Glazing remains a critical challenge for reducing embodied carbon**, as the process of producing glass requires a significant amount of heat and high-embodied-carbon materials for framing. Products available today can cut embodied carbon in glazing by approximately 25%, but at a 10% cost premium.
5. **Finish materials can serve as a key carbon-reduction or carbon-storage opportunity.** Case study 2 showed that preoccupancy finish materials (e.g., flooring, carpet tiles, ceiling tiles, and paint) can account for approximately 10% of project-level cradle-to-gate embodied carbon. Some of these elements are capable of >50% reductions at no up-front cost premium, and in some locales, carbon-sequestering materials may even be available.[37]

[i] Interior finish and fit-out reductions were included to a limited extent in case study 2; they were excluded from the other case studies because interior fit-out and finish materials were not included in the bill of materials for the original projects.
[ii] These changes were not considered in the case studies because they would have required a level of structural redesign beyond the scope of the project.
[iii] Because this analysis was based on buildings that had already been designed and specified, these changes fell outside the scope of the project.

Exhibit 6 **The categories in which a project's embodied carbon can be reduced for little to no cost**



Section 5
Opportunities to Drive Deeper Savings

Opportunities to Drive Deeper Savings

The case studies in Section 4 demonstrate that the technology and solutions available today can economically lower the embodied carbon of buildings. Although not a part of this study, there are several additional financial levers that could further improve the economics of low-embodied-carbon buildings:

- **Internal carbon pricing:** Applying a monetary cost to carbon via a carbon tax or self-induced corporate carbon pricing could dramatically increase the value of low-embodied-carbon design to the developer. Companies like Microsoft have implemented an internal cost of carbon that is used to influence decisions toward reducing carbon emissions, including construction carbon emissions.

- **Consumer savings:** Scaling production of low-embodied-carbon materials could result in cost savings being passed on to the consumer. Savings from reducing portland cement in a concrete mix, for instance, may today be realized only by the ready-mix supplier, but with added transparency and growing demand for concrete with lower cement content, these savings may become a benefit for the purchaser as well.

- **Market competition:** Increasing the production of low-embodied-carbon materials is likely to reduce the cost of the materials. This may also be accelerated by increased demand from preferential purchasing policies.

- **Developing and reducing embodied carbon targets:** Requiring the measurement of embodied carbon for new buildings and renovation projects alone will lead to greater demands for low-embodied-carbon materials and construction techniques. Once embodied carbon is regularly measured, codes, policies, and standards will become stronger tools for setting stringent targets. This will in turn reduce costs as a result of greater market penetration, familiarity, and production of critical products.

As the business case for low-embodied-carbon construction continues to grow and more practitioners adopt reduction strategies as standard practice, it is important to acknowledge key factors that can influence how low-embodied-carbon opportunities are approached in any given project.

Regional differences and data disparities may enable certain low-embodied-carbon solutions and prohibit others. **Emerging low-embodied-carbon materials and techniques** can make limiting embodied carbon simpler, less expensive, or more impactful as they become available. Finally, low-embodied-carbon **building codes and policie**s are gaining momentum across the United States and will increase market demand for low-embodied-carbon materials and construction.

Regional Differences

Regional variations in labor force, material supply availability, carbon intensity of energy grids, and other factors can significantly alter the economic viability, availability, and workforce capabilities around specific low-embodied-carbon solutions.

Electricity used during manufacturing can come from regional sources with varying degrees of carbon intensity. For instance, some steel products made in factories using electric arc furnaces can be very low in embodied carbon if the electricity comes from hydropower or other zero-carbon sources. In regions using coal and other carbon-intensive fuels to generate electricity, those same steel products will have much higher embodied carbon.

The transportation of materials within or across geographic regions can significantly impact the embodied carbon of a product. Although the manufacturing stage typically emits the highest levels of carbon in the life cycle of a given product, transportation emissions can be substantial, particularly when a large quantity of material is transported across long distances. When evaluating low-embodied-carbon material options, emissions associated with transport to the construction site (lifecycle stage A4) should be considered alongside the embodied carbon of the given material (lifecycle stages A1–A3). It is worth noting that many studies, including this study, do not incorporate lifecycle stage A4 because the information is not readily available via tools such as EC3. Additionally, it requires an additional side calculation for each material depending on its source. In some cases, specifying local materials that cut down on transportation emissions will be the better option, whereas in other cases it will be better to ship materials with low up-front embodied carbon from farther away.

The capability of a local labor force to work with low-embodied-carbon products varies, affecting a design and construction team's ability to implement certain low-embodied-carbon solutions. Many products—such as low-embodied-carbon carpet tiles, thinner wall gypsum boards, and sustainably sourced sheathing products—look, feel, and are typically installed like their traditional counterparts. However, constructing a mass timber structural system or working with a new cement chemistry may be a skill set less common to a given region, which can risk additional time and expense for a project that specifies these solutions without a trained and knowledgeable workforce.

The negative impacts of regional differences will decrease as demand grows for low-embodied-carbon products, labor forces gain experience with new skill sets and construction methods, and training becomes available to work with these materials and solutions.

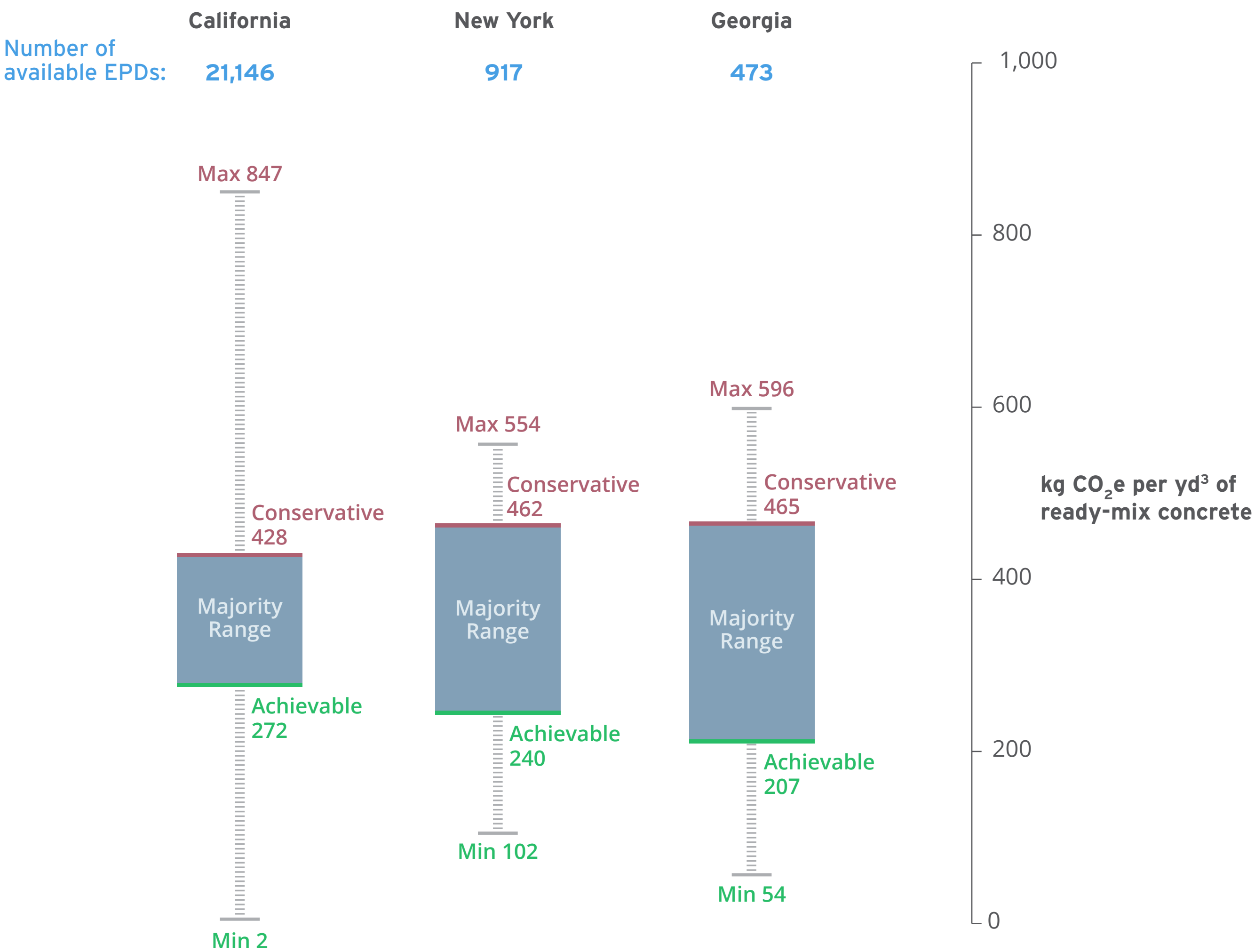
Regional Data Disparity

Environmental Product Declarations (EPDs) are a key tool for selecting low-embodied-carbon products. The availability of EPDs varies by region due to manufacturers supplying data based on demand from the local public and private sectors.

The graphs below (Exhibit 13) show the range of embodied carbon content in ready-mix concrete from EPDs across California, New York, and Georgia. The highest value within the colored area indicates that 80% of products represented have less embodied carbon than the value listed, demonstrating a conservative target for reduction. A tighter, but still achievable target is demonstrated by the lowest value within the colored area, indicating that only 20% of products represented have less embodied carbon than the value listed. This range is similar across all locales, whereas the extreme minimum and maximum values vary significantly, indicating that some regions, such as California, have a higher number of EPDs that show a wider range of products.

Exhibit 7 Embodied carbon range of ready-mix concrete available in California, New York, and Georgia

In each location, the "Conservative" value represents that 80% of available EPDs show a lower embodied carbon content per unit of concrete, the "Achievable" value represents that 20% of EPDs show a lower value, and the "Majority Range" captures 60% of available EPDs.



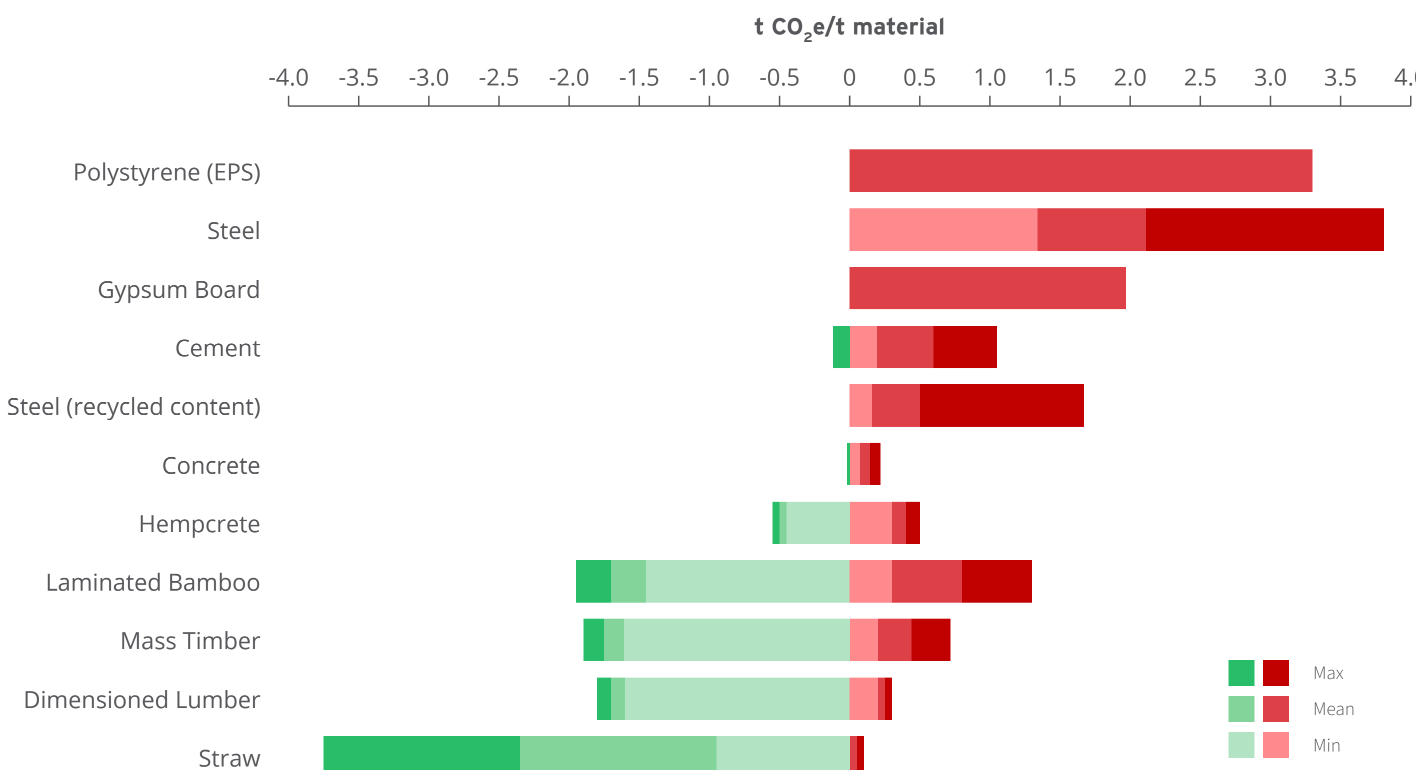
Source: EC3 Tool

Advanced Materials to Drive Greater Change

Emerging low-embodied-carbon materials and techniques can make limiting embodied carbon simpler, less expensive, or more impactful as they become available. Although embodied carbon can be reduced substantially using widely available products today, emerging materials and other technologies may help lower embodied carbon content as they become available, prove their merit, or come down in price. Exhibit 8 demonstrates a wide array of building materials (most of which are readily available today) that range from high-embodied-carbon materials to materials with high net embodied carbon storage potential. Raising awareness around readily available materials that either reduce or (net) store embodied carbon alone can dramatically curb building-related carbon emissions.

The materials outlined in Exhibits 9–11 demonstrate a variety of embodied carbon reduction measures and offer alternatives to traditional construction materials with higher embodied carbon. While some materials are widely available across the United States, others are emerging and require further testing. It is critical to research the embodied carbon savings offered by a given material along with specific constructability, durability, cost, and other factors when choosing advanced material options.

Exhibit 8 **CO_2e emissions and storage capacity of building materials**



Source: Table S6, Galina Churkina et al., "Buildings as a Global Carbon Sink," Nature *Sustainability*, 2020

Exhibit 9 **Market-Ready Materials**

Materials that are readily available but have not yet achieved high market penetration

Embodied Carbon Reduction Measure	Description	Market Readiness
Carbon-negative carpet backing	By increasing the quantity of pre- and post-recycled materials, biopolymers, and other bio-based materials, carpet tile manufacturers can produce products that are carbon negative when measured from cradle to gate.	Products are readily available for use today.
Plant-based insulation products	A growing number of plant-based insulation products are available on the market. These materials are often considered low in embodied carbon or provide a net sequestration of carbon in buildings. Cellulose has been available for decades in the United States but is being reformulated to work in different form factors. Hempcrete is another highly sustainable material that serves as an excellent insulator. Both of these materials are available in the residential market but are not readily available in the in commercial construction market.	Several straw, hempcrete, and cellulose products are available on the market today.
Next-gen, low-GWP XPS insulation products	Low-GWP extruded polystyrene (XPS) insulation products are made by replacing HFC-134a, a high-GWP hydrofluorocarbon blowing agent, with a blend of other blowing agents with lower GWPs. The blends do not eliminate GWP but offer a lower alternative to traditional XPS products with very high GWP.[38]	Several products are available in the United States.
Graphene-infused carbon-sequestering paint	Graphene-infused paints are lime-based products with added graphene for strength and durability. The lime ingredient absorbs CO_2 from the surrounding air as the paint dries.	Several products are available in the United States, but their carbon reduction claims are untested.
Lightweight wallboard products	Lightweight wallboard products reduce transportation emissions and are more easily handled on job sites. One example is a lightweight gypsum board that also reduces embodied carbon by requiring less heat and associated emissions needed to dry the mix. It also uses less water than typical gypsum wallboards.[39]	Several products are available in the United States.
Type 1L cement products	The use of limestone as a supplementary cementitious material (SCM) represents an important, low-cost, high-availability first step toward lowering the embodied emissions of concrete. Limestone is the most readily available SCM, given that it is already present in cement and deposits are widely available. The total emissions abatement potential of limestone is limited by substitution limits (15% in ASTM), which reflect the reduction in strength associated with use of limestone as an SCM.	Several products are available in the United States.

Exhibit 10 Near-Market-Ready Materials

Materials that are available on a small- or pilot-project scale but are not yet broadly available on the market

Embodied Carbon Reduction Measure	Description	Market Readiness
Alternative cement chemistries and processes	Several emerging cement chemistries and production methods are being pursued, requiring less fuel for cement production and resulting in fewer chemical reaction emissions. Some of these technologies are currently in use in a limited number of production facilities for ready-mix concrete, others are currently being used only to make precast pavers, and others are earlier in development.	Market readiness varies based on the technology and the producer. Most products have undergone testing and are currently being offered by one or more ready-mix concrete suppliers.
Higher concentrations of SCMs in concrete	Substituting cement with supplementary cementitious materials (SCMs), such as fly ash, slag, or pozzolanic materials, in higher percentages can drive greater carbon reductions. SCMs from non-fossil fuel sources such as glass pozzolan or rice husks can further enhance carbon reductions. This substitution leads to lower cement requirements in the concrete mix but is dependent on the supply of SCMs, availability of high SCM mix design performance data, and architectural/structural design requirements. Higher concentrations of SCMs than are typically accepted by industry today can increase the time to reach specified compressive strengths, which is why this strategy is typically limited or not used at all for quick vertical construction projects with short timelines.	Producers are consistently looking for ways to reduce cement content in concrete mix by increasing the amount of SCMs, but high (50%-plus) SCM mixes are not currently market validated in most regions.
CO_2-injected cement products	These products claim to reduce embodied carbon by directly injecting carbon dioxide into concrete, where it is mineralized and permanently embedded. Since cement naturally carbonates over time, it remains unclear whether this process offers long-term carbon advantages, particularly given the need for high-grade CO_2. Some companies are also looking at capturing CO_2 from cement kilns.	These products are available in certain locales, but their embodied carbon reduction claims are untested.
Plant-based wall panels	SIPs and other exterior panels can be made with plant-based materials. Some carbon accounting systems may consider these materials to be net carbon sequestering, and others would consider them to be low embodied carbon when compared with the petroleum- or gypsum-based traditional materials that they replace.	Straw bale SIPs and prefabricated straw bale wall panels have been successfully implemented in the residential market for selective projects; however, these applications are not yet common in the commercial market.
CO_2-sequestered aggregates for concrete	This new technology uses CO_2 as a raw material for making carbonate rocks. The carbonate rocks produced are used in place of natural limestone rock mined from quarries, which is the principal component of concrete.	Several startups are actively developing this new technology.
Magnesium oxide wallboard	Magnesium oxide wallboards can be used in place of traditional gypsum drywall or other sheathing applications. The calcination process required to manufacture this product occurs at lower temperatures compared with that of traditional portland cement or calcium oxide, resulting in reduced manufacturing emissions.	Several US manufacturers offer products with a variety of applications and uses, but some studies have highlighted negative moisture-absorbing features that can lead to mold and moisture damage in certain cases.[40]
Laminated bamboo lumber and structural bamboo	Bamboo lumber products are a viable alternative to lumber. Bamboo offers some advantageous strength characteristics compared to typical lumber products, but there are outstanding questions about the longevity and general resilience of bamboo lumber products.[41]	Not tested or produced at scale in the United States

Exhibit 11 Materials in Development

Materials that are under development and that could provide significant embodied carbon reductions for critical building materials

Embodied Carbon Reduction Measure	Description	Market Readiness
Zero-carbon steel	Using molten oxide electrolysis or renewably produced hydrogen to produce steel and reducing the amount of virgin steel through reuse or recycling can enable a zero-carbon steel product. Currently, lower-embodied-carbon steels are available, but there is not a market-ready zero-carbon steel.[42]	This product is not yet available on the market, but many producers are improving the embodied carbon of available steel year-over-year, and there are active efforts to produce zero-carbon steel in the United States and Europe.
Glass pozzolan SCMs	SCMs can be made from recycled glass products, which proponents claim improves performance of the ultimate concrete mix.	There are several emerging companies working in conjunction with local recycling centers to bring glass pozzolan SCMs to market. The greatest limits are due to economics and availability of the SCMs.
Cement production powered by alternative fuels	Using alternative fuels for the heating process during the production of clinker for ordinary portland cement would address approximately 40% of the current up-front embodied carbon of cement production. This is technically achievable but has not been tested at a large scale. The process would not address the emissions related to chemical processes.	This is still in the early stages of development.
Self-healing and living materials	Self-healing materials, including concrete, can reduce embodied carbon by increasing the longevity of certain materials with lives that are limited by material failure. Some living materials can further reduce embodied carbon by sequestering carbon dioxide from the atmosphere in the process of forming.[43]	Most self-healing and/or living materials are in early stages of laboratory development.

Codes and Policy

A growing number of codes and policies are targeting embodied carbon reductions across city, state, and federal levels. Codes, standards, regulations, and incentive programs can all be effective tools for driving change by promoting and establishing best practices to reduce embodied carbon in construction.

Already we have seen several low-embodied-carbon policies put into effect, including the Buy Clean California Act. The policy drives low-embodied-carbon procurement by requiring contractors bidding on state infrastructure and construction projects to disclose the Environmental Product Declarations (EPDs) of certain materials and mandates a preference for lower-carbon products. Buy Clean California has inspired several other state legislatures to pursue similar policies.

Further, in 2021 the US General Services Administration approved an advice letter recommending two key strategies to limit embodied carbon in the federal government:[44]

1. The first strategy, a material approach, applies to all projects. This approach requires EPDs for 75% of materials used in a project and requires that their emissions rank in the best-performing 80% in terms of global warming potential among functionally equivalent products.
2. The second strategy is a whole-building life cycle assessment (WBLCA) approach, applicable to larger projects over $3.095 million. The WBLCA approach requires that the life cycle assessment of a building's design shows at least a 20% carbon reduction, as compared with a baseline building.

These policies aim to reduce demand for high-embodied-carbon products through preferential purchasing of low-impact materials. The Athena Sustainable Materials Institute highlights a number of other approaches to limiting embodied carbon through codes and policies,[45] including:

- Other financial incentives, such as bid incentives or tax credits
- Transparency initiatives such as requiring or incentivizing the measurement and disclosure of embodied carbon data for building projects
- Performance approaches such as requiring or incentivizing the reduction of embodied carbon for building projects relative to:
    - A customized performance target defined by a benchmarking system
    - A fixed performance target related to the GWP of a building or material
- Prescriptive approaches such as requiring or incentivizing the use of specific materials or design measures

While these code and policy solutions have shown to be effective in select contexts, this is not an exhaustive list. A report by the Carbon Neutral Cities Alliance, *City Policy Framework for Dramatically Reducing Embodied Carbon,* demonstrates the wide-ranging scope of embodied carbon reduction policies by outlining 52 policies spanning five categories: zoning and land use, building regulations, procurement, waste and circularity, and financial policies.[46] New proposals for these types of legislation, as well as governmental commitments such as C40 Cities' Clean Construction Declaration, are gaining momentum across the United States. In addition to governmental policies, corporations are issuing policies on a monthly basis that limit embodied carbon.

Section 6
Conclusion

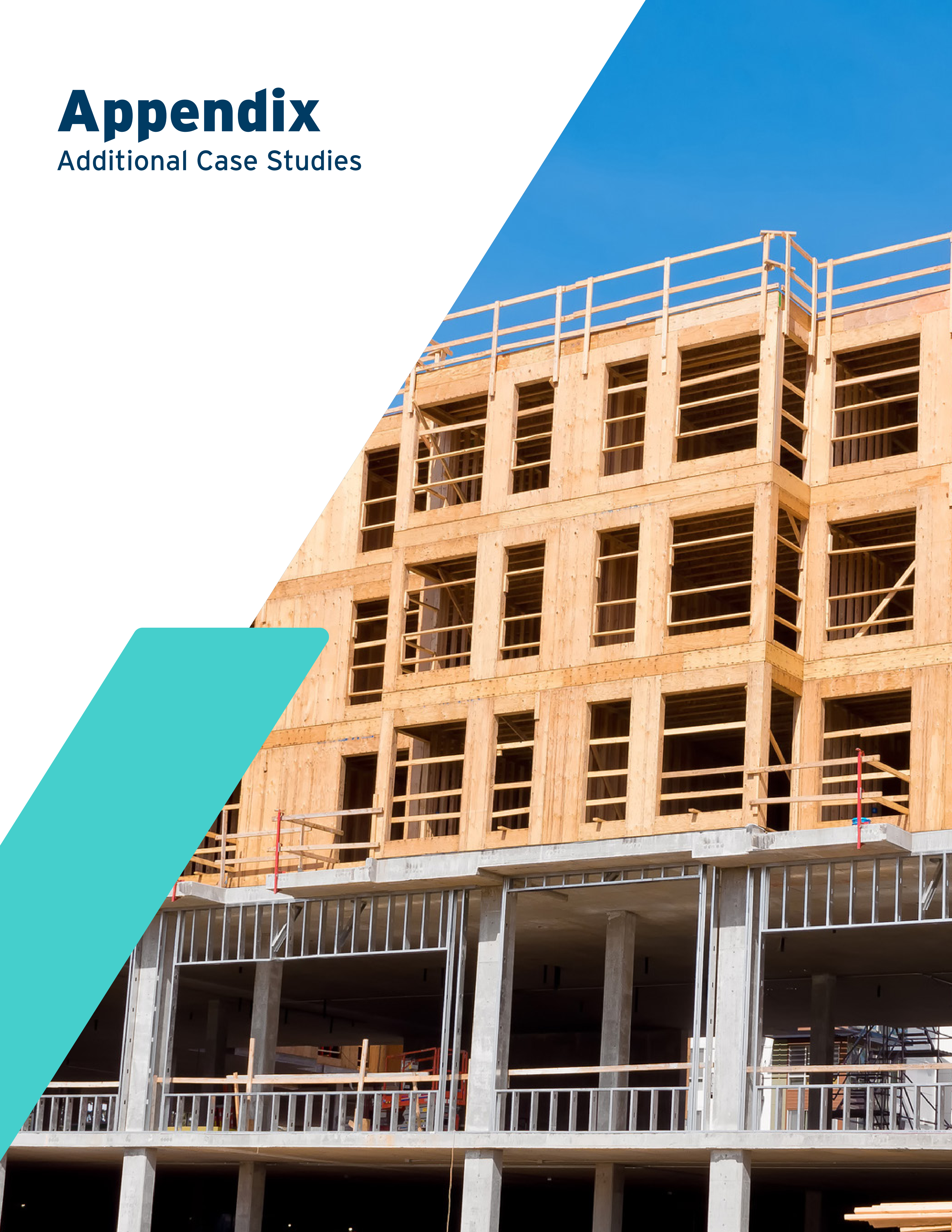
Conclusion

Reducing embodied carbon is an urgent and critical issue, because the trajectory of embodied carbon emissions is not currently aligned with global climate targets. Since 2010, as global emissions from building operations have decreased slightly, construction-related emissions have actually increased by 1.5%.[47] **It is imperative that practitioners employ the strategies and solutions available today to accelerate the adoption of low-embodied-carbon construction.** These changes are necessary to deliver the unprecedented action required to meet the goal of the Paris Climate Agreement and limit global warming to 1.5°C.

This report demonstrates that midsized commercial building projects can reduce embodied carbon by up to 46% at less than a 1% cost premium using materials that are widely available today. The reductions highlighted by our three case studies are backed up by methods and materials that are widely available and simple to implement. Reductions can go well beyond 50% by considering whole-building design strategies, incurring a higher cost premium, or leveraging some of the advanced materials that are coming down the R&D pipeline. The technologies that enable low-embodied-carbon construction will continue to evolve, and regional nuances will continue to influence the efficacy of individual products or solutions. But **the design methods and high-level considerations highlighted in this report can be applied to any project today, offering lasting solutions to eliminate and sequester carbon emissions in our buildings.**

Appendix

Additional Case Studies



APPENDIX: Additional Case Studies

The case studies below were compiled while conducting research for this report and are included here for additional insight into the impacts of various approaches to lowering the embodied carbon content of low- and mid-rise buildings.

Exhibit A1 Additional Case Studies

Construction Type	Study Name	Location	Building Typology	Size (ft^2)	Link
Mid-rise steel and concrete	Tally case study	Seattle, WA	Residence halls at the University of Washington	size not listed	https://choosetally.com/casestudy/
Mid-rise steel and concrete	Case study 1 from "Mass Timber Optimization and LCA," Carbon Leadership Forum (CLF)	WA	9-story commercial building	size not listed	https://carbonleadershipforum.org/mass-timber-optimization-and-lca/
Concrete tilt-up	Panelized Roof Systems, Woodworks	CA, WA, OR, HI	Commercial buildings	various	https://www.woodworks.org/wp-content/uploads/IS-Panelized-Roofs.pdf
Mid-rise mass timber (CLT)	LCA of Katerra's CLT and Catalyst Building, CLF	Spokane, WA	5-story office building	168,800	https://carbonleadershipforum.org/katerra/
Mid-rise mass timber (CLT and glulam)	Comparative Life-Cycle Assessment of a Mass Timber Building and Concrete Alternative	Portland, OR	12-story mixed-use apartment/office building	89,986	https://www.fpl.fs.fed.us/documnts/pdf2020/fpl_2020_liang001.pdf
Mid-rise wood frame	Luxury Wood-Frame Apartment Community Completes Dense, Mixed-Use Urban Development, Woodworks	Atlanta, GA	5-story, wood-frame apartment buildings (3 buildings)	275,000	https://www.woodworks.org/wp-content/uploads/CrescentTerminus_CaseStudy.pdf

Endnotes

Endnotes

1. *Bringing Embodied Carbon Upfront: Coordinated Action for the Building and Construction Sector to Tackle Embodied Carbon,* World Green Building Council, 2019, **https://www.worldgbc.org/sites/default/files/WorldGBC_Bringing_Embodied_Carbon_Upfront.pdf**; and Robert James Pratt, "A Common Ask: Collecting ESG Data on Building Materials, Starting with Embodied Carbon," *Urban Land*, January 31, 2021, **https://urbanland.uli.org/sustainability/a-common-ask-collecting-esg-data-on-building-materials-starting-with-embodied-carbon/.**

2. Kathrina Simonen, Barbara X. Rodriguez, and Catherine De Wolf, "Benchmarking the Embodied Carbon of Buildings," *Technology | Architecture + Design 1*, no. 2 (2017): 208–218, **https://doi.org/10.1080/24751448.2017.1354623.**

3. *Sustainability of Construction Works—Assessment of Buildings, Part 2: Framework for the Assessment of Environmental Performance*, European Committee for Standardization, 2011.

4. "New Buildings: Embodied Carbon," Architecture 2030, accessed April 1, 2021, **https://architecture2030.org/new-buildings-embodied/.**

5. Lizhen Huang et al., "Carbon Emission of Global Construction Sector," *Renewable and Sustainable Energy Reviews 81* (January 2018): 1906–1916, **https://doi.org/10.1016/j.rser.2017.06.001.**

6. Bringing Embodied Carbon Upfront, World Green Building Council, 2019.

7. *The Critical Role of Buildings*, IEA, 2019, **https://www.iea.org/reports/the-critical-role-of-buildings#highlights.**

8. *Embodied Carbon in Building Materials for Real Estate*, Urban Land Institute, 2019, **https://americas.uli.org/wp-content/uploads/ULI-Documents/Greenprint-Embodied-Carbon-Report_FINAL.pdf.**

9. *Centering Equity in the Sustainable Building Sector: Comprehensive Summary: CESBS Launch Summit* NAACP, 2018, **https://naacp.org/wp-content/uploads/2020/04/CESBS-Summit-Comprehensive-Summary_July-2019.pdf.**

10. Paula Melton, "The Urgency of Embodied Carbon and What You Can Do about It," *BuildingGreen*, September 10, 2018, **https://www.buildinggreen.com/feature/urgency-embodied-carbon-and-what-you-can-do-about-it.**

11. Colin R. Gagg, "Cement and Concrete as an Engineering Material: An Historic Appraisal and Case Study Analysis," *Engineering Failure Analysis* 40 (May 1, 2014): 114–140, **https://doi.org/10.1016/j.engfailanal.2014.02.004.**

12. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2018*, US Environmental Protection Agency, 2020, https://www.epa.gov/sites/production/files/2020-04/documents/us-ghg-inventory-2020-main-text.pdf; and "Manufacturing Energy and Carbon Footprint," US Department of Energy, **https://www.energy.gov/sites/prod/files/2018/10/f56/2014_mecs_cement_energy_footprint.pdf.**

13. Gagg, "Cement and Concrete as an Engineering Material," 2014; and Inventory of U.S. *Greenhouse Gas Emissions and Sinks*, US Environmental Protection Agency, 2020.

14. "Supplementary Cementitious Material: An Overview," *ScienceDirect*, **https://www.sciencedirect.com/topics/engineering/supplementary-cementitious-material.**

15. *Embodied Carbon: A Clearer View of Carbon Emissions*, Walter P. Moore, 2020, **https://www.walterpmoore.com/sites/default/files/wpm_embodied_carbon_report_2020.pdf.**

16. "Supplementary Cementitious Material," *ScienceDirect*.

17. Thomas Czigler et al., "Laying the Foundation for Zero-Carbon Cement," McKinsey & Company, May 14, 2020, **https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement.**

18. *2019 U.S. Cement Industry Annual Yearbook*, Portland Cement Association, 2019, **https://www.cement.org/morereports/2018-us-cement-industry-annual-yearbook.**

19. *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, US Environmental Protection Agency, 2020.

20. "Manufacturing Energy and Carbon Footprint," US Department of Energy; and ibid.

21. Ali Hasanbeigi and Cecilia Springer, *How Clean Is the U.S. Steel Industry?* Global Efficiency Intelligence, 2019, **https://www.globalefficiencyintel.com/us-steel-industry-benchmarking-energy-co2-intensities.**

22. *Profile of the American Iron and Steel Institute, American Iron and Steel Institute*, 2019, **https://www.steel.org/industry-data/reports/**; I*nventory of U.S. Greenhouse Gas Emissions and Sinks*, US Environmental Protection Agency, 2020; and "Manufacturing Energy and Carbon Footprint," US Department of Energy.

23. Jeffrey Tomich, "U.S. Readies First Wind-Powered Steel Plant," *E&E News*, November 15, 2019, **https://www.eenews.net/stories/1061552453.**

24. "ENERGY STAR Focus on Energy Efficiency in Iron and Steel Manufacturing," Energy Star, https://**www.energystar.gov/industrial_plants/measure-track-and-benchmark/energy-star-energy-5.**

25. *Structural Steel: An Industry Overview*, American Institute of Steel Construction, August 2018, **https://www.aisc.org/globalassets/aisc/publications/white-papers/structural_steel_industry_overview_2018.pdf.**

26. "Forest Management Certification," Forest Stewardship Council, **https://fsc.org/en/forest-management-certification.**

27. James L. Howard and Shaobo Liang, "United States Forest Products Annual Market Review and Prospects, 2015–2019," US Department of Agriculture, **https://unece.org/fileadmin/DAM/timber/country-info/statements/usa2018.pdf.**

28. "About – Carbon Smart Materials Palette," Architecture 2030, accessed March 30, 2021, **https://materialspalette.org/about/.**

29. *The Greenest Building: Quantifying the Environmental Value of Building Reuse*, National Trust for Historic Preservation, 2011, **https://forum.savingplaces.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=5119e24d-ae4c-3402-7c8e-38a11a4fca12&forceDialog=0.**

30. Larry Strain, "10 Steps to Reducing Embodied Carbon," AIA, **https://www.aia.org/articles/70446-ten-steps-to-reducing-embodied-carbon.**

31. Data from *2018 Commercial Buildings Energy Consumption Survey*, US Energy Information Administration, 2020, **https://www.eia.gov/consumption/commercial/data/2018/index.php.**

32. *Estimates of Embodied Carbon for Mechanical, Electrical, Plumbing and Tenant Improvements: Summary Document*, Carbon Leadership Forum, April 2019, **https://carbonleadershipforum.org/lca-of-mep-systems-and-tenant-improvements/.**

33. *Designing for the Future: Interior Life Cycle Analysis*, Hawley Peterson Snyder, February 7, 2020, **https://www.oneworkplace.com/assets/files/HPS-ONEder-Grant.pdf.**

34. *Estimates of Embodied Carbon for Mechanical, Electrical, Plumbing and Tenant Improvements: Summary Document*, Carbon Leadership Forum, April 2019.

35. *Designing for the Future*, Hawley Peterson Snyder, 2020.

36. *Life Cycle Assessment of a Commercial Tenant Improvement Project: Summary Document*, WeWork and Carbon Leadership Forum, October 2019, **https://carbonleadershipforum.org/lca-of-a-wework-tenant-improvement-project/.**

37. "Carbon Storing Carpet. It's a Thing," Interface, accessed March 17, 2021, **https://www.interface.com/US/en-US/sustainability/climate-take-back/carbon-storing-carpet-en_US.**

38. "Transitioning to Low-GWP Alternatives in Building/Construction Foams," US Environmental Protection Agency, 2011, **https://www.epa.gov/sites/production/files/2015-07/documents/transitioning_to_low-gwp_alternatives_in_building_and_construction_foams.pdf.**

39. "Gypsum Board – Carbon Smart Materials Palette," Architecture 2030, accessed March 30, 2021, **https://materialspalette.org/gypsum-board/.**

40. Marina Gravit et al., "Problems of Magnesium Oxide Wallboard Usage in Construction," *IOP Conference Series: Earth and Environmental Science* 90 (2017): 012103, **https://iopscience.iop.org/article/10.1088/1755-1315/90/1/012103/pdf.**

41. Lilly Cao, "How Effective is Laminated Bamboo for Structural Applications?" *ArchDaily*, February 29, 2020, **https://www.archdaily.com/934274/how-effective-is-bamboo-for-structural-applications.**

42. "MOE Technology," Boston Metal, accessed March 30, 2021, **https://www.bostonmetal.com/moe-technology/**; and Frédéric Simon, "Swedish Steel Boss: 'Our Pilot Plant Will Only Emit Water Vapour,'" *EURACTIV*, May 10, 2018, **https://www.euractiv.com/section/energy/interview/hybrit-ceo-our-pilot-steel-plant-will-only-emit-water-vapour/**.

43. Amos Zeeberg, "Bricks Alive! Scientists Create Living Concrete," *New York Times*, January 15, 2020, **https://www.nytimes.com/2020/01/15/science/construction-concrete-bacteria-photosynthesis.html.**

44. "GSA Green Building Advisory Committee Advice Letter: Policy Recommendations for Procurement of Low Embodied Energy and Carbon Materials by Federal Agencies," US General Services Administration, February 17, 2021, **https://www.gsa.gov/governmentwide-initiatives/federal-highperformance-buildings/policy/green-building-advisory-committee/advice-letters-and-resolutions.**

45. Jennifer O'Connor and Matt Bowick, "Reducing Embodied Environmental Impacts of Buildings: Policy Options and Technical Infrastructure," Athena Sustainable Materials Institute, December 2019, **http://www.athenasmi.org/wp-content/uploads/2019/12/Policy_white_paper_December_2019.pdf.**

46. *City Policy Framework for Dramatically Reducing Embodied Carbon: 52 Detailed Policies to Reduce Embodied Carbon*, Carbon Neutral Cities Alliance, One Click LCA, and Architecture 2030, 2019, **https://www.embodiedcarbonpolicies.com.**

47. "Delivering the Paris Agreement: The Role of the Built Environment," World Green Building Council, **https://www.worldgbc.org/sites/default/files/2050%20Letter%20Final.pdf.**

Matt Jungclaus, Rebecca Esau, Victor Olgyay, and Audrey Rempher, ***Reducing Embodied Carbon in Buildings: Low-Cost, High-Value Opportunities,*** **RMI, 2021,**
http://www.rmi.org/insight/reducing-embodied-carbon-in-buildings.

All images used are from iStock.com unless otherwise noted.

RMI Innovation Center
22830 Two Rivers Road
Basalt, CO 81621

www.rmi.org